Assessment of Concrete Strength by Lok and Capo Tests

by

Hamoud Abdulrab Mohammed Bishr

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

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This thesis, written by **HAMOUD ABDULRAB MOHAMMED BISHR** under the direction of his thesis committee, and approved by all the members, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfillment of the requirements for the degree of

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جامعة الملك فهد للبترول والمعادن

وقل رب زدني علما

1963 ١٣٨٣

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

بسم الله الرحمن الرحيم

وما أوتيتم من العلم إلا قليلا

بسم الله الرحمن الرحيم

وقل اعملوا فسيرى الله عملكم ورسوله والمؤمنون

صدق الله العظيم

In the name of God, Most Gracious, Most Merciful

Say unto them, work as ye will;
but God will behold your work,
and his apostle also, and
the true believers.

SURAT. AL TAWBAH

Dedicated to

My parents and brothers

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ملخـــــــــــص

من المعلوم ان مقاومة الخرسانه في المنشآت تختلف عن مقاومة الضغط للعينات المجهزة ونتيجة لذلك تزايد الطلب من أجل ايجاد طرق أخرى عملية ودقيقة ، لتحديد نوعية وقوة الخرسانه مما أدى الي تطوير اساليب حديثة لتقييم خواص الخرسانة ٠ من هذه الطرق أختبار شد الاقراص المعدنية والذى ينقسم الي قسمين أساسيين ٠:

النوع الاول و يتطلب وضع القرص المعدني في الشدة الخشبية قبل الصب (لوك) والنوع الثاني يمكن اجراءه في اى زمن بعد تصلب الخرسانه (كابو) ٠ وبواسطة هذا الاختبار نستطيع ان نوجد القوة المطلوبة لشد القرص المعدني الموضوع في الخرسانه ٠

ولهذا اجريت هذه الدرسه للحصول علي المعلومات الكافية التي يمكن بواسطتها معرفة مدى دقة هذه الاختبارات لا يجاد مقاومة الخرسانه في الموقع وكذلك لتطوير نماذج تقدير قوة الخرسانه باستعمال اختبار (لوك) واختبار (كابو) ٠ وهناك متغيرات مهمة تم دراسة تأثيرها علي هذه النماذج مثل الزمن ، نسبة الماء للاسمنت كمية الاسمنت ، نوع الحصي الخشن ٠

والعينات المستخدمة للدراسة عبارة عن صبيات خرسانية بسمك ١٥٠ مليمتر وكذلك اسطوانات يبلغ قطر الواحد منها ٧٥ مليمتر بالاضافة الي القلوب الخرسانية المأخوذة من هذه الصبيات ٠

بناء علي التحليل التراجعي لمعلومات الاختبار المستخلصة تم دراسة تأثر المتغيرات المختلفة على مقاومة الخرسانة ، وكذلك رسم العلاقات بين كل من اللوك ، الكابو و مقاومة الخرسانه الناتجة من اختبار الاسطوانات السابقة ٠

وكذلك تم التحقق من صحة ومدى الاعتماد علي هذه النماذج المقترحة و ذلك عن طريق مقارنه قوة الخرسانه المتوقعة مع القوة الفعلية للخرسانه ٠

ABSTRACT

NAME : *HAMOUD ABDULRAB MOHAMMED BISHR*

TITLE : *ASSESSMENT OF CONCRETE STRENGTH BY LOK AND CAPO TESTS.*

MAJOR FIELD : *CIVIL*

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It is recognized that strength of concrete in structures is different than strength of control specimens, therefore an increased demand for more precise and more practical methods of in-situ assessment of concrete quality had led to the development of a large variety of techniques to evaluate concrete properties, such as strength, durability and quality control.

Pullout testing of concrete is one of these techniques which divides into two basic categories; the first one has an insert which is cast into the concrete (lok-test), the other has an insert fixed into a hole drilled into the hardened concrete (capo-test).

The purpose of this study is to verify the accuracy and reliability of lok-test and capo-test methods for estimation of in-situ compressive strength of concrete made with commonly used local materials, and to develop the necessary calibration curves between pullout force and standard compressive strength for various types of aggregates, cement contents and water cement ratios.

Based on a regression analysis of the generated data, effects of the previous variables on the behavior of strength have been studied and the calibration curves developed.

The proposed models have been verified for their reliability by comparing predicted strength with the actual strength.

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CHAPTER 1

INTRODUCTION

1.1 General

The structural quality of concrete is not easily controlled since it is greatly affected by the quality and proportioning of its component materials and by the environmental conditions under which its curing takes place. Compressive strength is an excellent indication of concrete quality and it forms the most important basis of a specification, as many other properties of concrete are directly or indirectly related to it.

In the standard method for determining the strength of concrete, specimens of the hardened material are tested to failure in compression, with the specimens prepared from fresh concrete samples. The standard compressive strength test undoubtedly constitutes an excellent means for quality control of concrete. In addition, it is commonly use to estimate other mechanical properties of concrete such as tensile strength, modulus of elasticity ...etc. However, the standard compressive strength has some limitations. Briefly, these consist of inherent errors in sampling and the fact that concrete in structure is placed, compacted ,transported and cured differently from that cast in cylinders or cubes.

To overcome the limitations of the standard strength test, considerable effort has been made in the past to develop other testing methods, particularly of a non-destructive nature, that would permit the evaluation of quality of concrete and its behaviour in the structure.

Over the past few decades, nondestructive testing of concrete has received increasing acceptance for evaluation of strength, properties and uniformity of in-situ concrete; such testing has been necessary either as part of a quality assurance program or as part of a diagonistic evaluation of the causes of concrete problems with regard to durability, cracking and compliance to a prescribed specification.

The nondestructive testing methods provide an effective way of obtaining considerable amount of test data at a relatively little cost and short time, which is considered to be a major advantage. Although nondestructive tests are relatively simple to perform, the analysis and interpretation of the test data are not so easy because concrete is a complex material, so the interpretation of the test data must always be carried out by specialists in this field.

For the past 30 years work has been going on to find methods permitting determination of in-situ strength of concrete in the structure itself. One method which has been found to be an acceptable to many of the concrete testers is the pullout method. The pullout test measures the force required to pull out test bolts embedded in the structure, after which an empirically established relationship is used for conversion of the measurements to the cylinder compression strength of the concrete.

1.2 Research Significance

A need for a reliable non-destructive method to determine in-situ concrete strength with a minimum damage and to satisfy simplicity of application, less cost, fast operation and direct measurements of strength. Also to establish pullout and compressive strength relationships by using local materials for the mixes.

1.3 Objectives of the study

ASTM and other specifications require that calibration curves for lok and capo tests should be developed for local materials and environmental conditions to convert their measurements into in-situ equivalent concrete strength. The overall objective of this study is to make use of the statistical analysis to develop calibration curves for converting Lok and Capo test measurements to equivalent conventional concrete strength. Data are generated in the laboratory from application of lok and capo tests on concrete panels and concrete cylinders made with different aggregate types and materials proportions. The main objectives of this research are as follows:

(1) To verify the accuracy and reliability of lok-test and capo-test methods for estimation of in-situ compressive strength of concrete made with commonly used local aggregates.

(2) To develop the necessary calibration curves between pullout force and standard compressive strength for various types of aggregates, cement contents and water cement ratios.

(3) To undertake an elaborate experimental program to generate sufficient amount of test data of lok and capo test for the purpose of modelling.

This study is being restricted to laboratory tests on standard 75 * 150 mm (3 * 6 in.) cylinders and 750 * 500 * 150 mm panels of concrete made from Jabal Dhahran and Abu-Hadriyah crushed aggregate, which are typical of Eastern Province coarse aggregates. The maximum size of coarse aggregate is 20 mm (3/4 in.), different water-cement ratios, and cement contents will be used.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of the Pull-out Tests

It is increasingly being recognized that strength of concrete in structures should be measured by in situ testing. Hence, an increased demand for more precise and practical methods to assess concrete quality has led to the development of a large variety of techniques to evaluate concrete properties, such as strength, durability and quality control.

These techniques attempt to measure some of the properties of concrete from which an estimate of strength, durability and its elastic parameters are obtained. Based on properties such as hardness, resistance to penetration, and the propagation of the ultrasonic pulse, various nondestructive methods of testing concrete have been developed such as rebound method, penetration techniques, pulse velocity methods and pullout test. In recent years, a combined methods approach (22) in which more than one nondestructive method is used to estimate strength of concrete have been proposed to increase the degree of reliability.

Of the nondestructive tests available, the pullout tests appear to have the best potential for acceptance as a measure of the compressive strength of in-place concrete. The pullout techniques, which are relatively new, are specially designed for in-situ testing of concrete and, unlike most other non-destructive methods, offer the advantage of direct determination of some strength parameters. In addition, these techniques show a good degree of correlation with the standard strength. Briefly, the pullout tests measure the force required to pull an embedded anchor plate out of the concrete. Because of the shape of the pullout assembly, a small cone of concrete is extracted (9).

Pullout testing of concrete is used to determine the strength of concrete placed and cured under actual field conditions. It has the advantage once the concrete has reached a specified strength level so that, for example, post-tensioning may take place, forms or shores be removed, winter protection terminated.

Pullout testing is also used to evaluate dubious structural elements prior to repair or load testing, and to check the joint effects of fresh concrete transportation, casting, consolidation, ambient temperature, and curing condition,on the structure by comparing the in-situ strength and variation with the results of standard compression tests as measured at the ready-mix plant under ideal laboratory conditions (8).

Pullout testing is not a recent development. It has been in use in USSR since 1935 (4).In the early 1970's, Richard and Malhotra published data on tests made with apparatus based on designs by Richard. In 1973 the North Carolina State Highway Department carried out some pullout tests. In 1977, as part of a National Research Council of Canda a study had been made by Bickly(1). The pullout test has been standardized in USA, where ASTM published a test method C900-78 for determining the pullout strength of concrete (28). During the years 1960-70, P.Kierkegaard-Hansen (Denmark) developed the Lok-test method, and many years ago, C.Germann Petersen (Denmark) developed the so-called Capo-Test.

Several studies (2,16,18,20,29,30,31,32) show that a significant correlation exists between the compressive strength of cylinders cured under standard conditions and the pullout strength of concrete. It is found that for the same concrete mix, the pullout strength increased with increasing age, indicating the possible usefulness of these tests for comparative studies.

Other studies have been performed to determine the concrete material properties which are measured by the pullout force. One of them was made by Malhotra and Carette (2), in which they presented comparisons of pullout strength of concrete with compressive strength of cylinders and cores, pulse velocity and rebound number. In this study, the water-cement ratio was varied from 0.36 to 0.70 and the corresponding cement contents varied from 845 to 390 lb/cubic yd. for each mix, one 24 * 24 * 12 in. (610 * 610 * 305 mm) concrete block, nine 4 * 8-in. cylinders, and three 6 * 12 in. cylinders were cast. The pullout tests on the concrete blocks were made at 7, 28, and 91 days. The blocks were also subjected to tests by the Schmidt rebound hammer, and pulse velocity measurements were taken. In addition, 4 * 8 in. cores were drilled from the blocks at the above ages. The cores along with the companion moist-cured test specimens were tested in compression (2).

at 7, 28, and 91 days, three 4 * 8 in. cylinders were capped with a sulfur and tested in compression; at

28 days, three 6 * 12 -in. were also tested in compression. Before capping, the pulse velocity was measured through the cylinders with pulse path being 12 in.

The relationships between the pullout strengths, compressive strengths of cylinders and drilled cores, rebound numbers and pulse velocity together with other comparisons are shown in Fig. 2.1 to 2.5, Where possible regression lines have been fitted to the test data.

Malhotra and Carette reported that the state of stresses in the pullout test is difficult to analyze and the magnitude of strengths obtained in this test indicates that perhaps the test measures the direct shear strength of concrete.

By using Coulomb's criterion for sliding failure, Jensen and Braestrup (23) showed that the pullout force is directly proportional to the compressive strength of the concrete.

By a finite element analyses of the failure mechanism Ottosen (10) concludes that large compression forces run in a rather narrow band from the embedded disc towards the reaction ring, so that the failure is caused by crushing of the concrete, not by cracking, which means that the pullout strength depends on the compression strength.

Bickley in his study (2) concluded that there is a high degree of correlation between the pullout force and the compressive strength, and stated that it is likely that the pullout test measures a property of the concrete that is either the compressive strength itself or that has a constant relationship with this.

Stone and Carino (11) conducted an experimental study using a large-scale pullout test, and concluded that the failure occurs in the form of shear failure of the matrix and aggregate interlock, starting at about 80% of the ultimate load.

According to krenchel and Petersen (8), there is no doubt that the failure in a Lok-Test and a Capo-Test is a compressive failure; the straight-lined correlations clearly indicate this, but the stress propagation during pullout is probably complex, involving triaxial compressive stresses.

In a test program conducted in 1975 (16), the lok-strength was compared with the Capo-strength in the surface of a 20 cm slab. On the basis of 20 tests of each type made on concrete with 16 mm maximum size sea gravel aggregates, it was found that the average pullout-forces were 25.9 kN for lok-test and 24.1 kN for capo-test with coefficients of variation of 4.6 and 5.3 , respectively.

In 1979, the Structural Research Laboratory of the Technical University of Denmark (16) conducted a research project to evaluate the reliability and reproducibility of the Capo-Test relative to Lok-Test and to the cylinder compressive strength. It has been found that a straight line relationships between lok-test or capo-test and cylinder compressive strength with coefficients of correlation of .96 for both tests.

A survey by Krenchel and Petersen (8), on the basis of a total of 24 major calibration series carried out in Denmark, Canada, USA, Sweden, Norway, and the Netherlands, was conducted and they found that calibrations to cylinder compressive strength and to cube compressive strength are unaffected by such variables as water-cement ratio, type of cement, age, curing conditions, form, size and source of aggregates, air entrainment, and admixtures. They also stated that the calibration curves obtained in their study demonstrate great stability from laboratory to laboratory, from site to site, and from country to country.

They summarized all calibrations made up to 1984 in Table 2.1, giving author, year of publication, number and type of reference specimen, number and position of pullout test, variable investigated, correlation found between pullout force and cylinder strength,maximum aggregate size, standard deviation and coefficient of variation, and coefficient of correlation.

Fig. 2.6a shows the correlations given in Table 2.1, and Fig. 2.6b shows the recommended calibration between pullout force and the cylinder compression strength. The calibration equations are:

(1) $P=0.96F_c+1.00$ for $2kN<P\leq 25kN$

(2) $P=0.8F_c+5.00$ for $25kN<P\leq 65kn$

Where the pullout force P is measured in kN and the cylinder strength F_c in MPa (8).

Also Table 2.2 summarizes the major calibrations developed by many researchers, comparing pullout force to 150 mm cube compressive strength. Fig. 2.7a illustrates the correlations found, and fig. 2.7b gives the recommended calibration, together with the 95 confidence limits The recommended equation has been found to be:

(3) $P = 0.75F_c + 2.20$ for $3kN < P \leq 65kN$

Where the pull force P is measured in kN and the cube strength Fc in MPa.

In a study (2), Malhotra had investigated the relationship of the pullout strength to the strength of the companion cylinders only and concluded that the pullout test is satisfactory for estimating the strength of in-situ concrete at both early and late ages and this test is superior to many nondestructive tests because a greater depth and volume is tested.

Bickley (12) discussed the use of pullout testing to achieve safety and economy in construction. He stated that pullout testing can provide an economic way of obtaining adequate numbers of tests from which statistically valid calculations can be made.

A comparative study (18) of five nondestructive apparatus for testing hardened concrete in place had been made by Nasser and Al-Manaseer. The apparatus are the pullout tester, the rebound hammer, the ultrasonic pulse velocity and the penetration probe. They found that linear and power regression equations were best suited to fit most of the data and to relate it to the compressive strength of the concrete.

Khoo (4) in his study presented of investigation on a pullout technique for the determination of in-situ strength of concrete. a minimum of twelve 150-mm cubes and two 600-mm cubical blocks were made from each of five mixes. In this study, a total of two hundred and seventy-six pullout tests were performed together with one hundred and thirty-five 150-mm standard cubes and ninety-two cores. At each age, six pullout tests and two cores tests were made at the same elevation on the cubical block and their respective averages calculated. The corresponding cube strength was obtained by taking the average of three cube strengths. The relationship between the pullout force and the compressive strengths of 150-mm cubes and 100 * 200 mm drilled cores are shown in Fig. 2.8a,2.8b . The pullout test results obtained indicated good correlation with the strength results obtained on drilled cores and standard-cured cubes.

Krenchel and Bickley (21) performed a study by using different pullout systems and examined the stress-strain distribution inside the concrete. They reported that the internal rupture pullout test is a multi-stage process, where three different stages can be identified. In the first stage, tensile cracks are formed starting from the upper edge of the pullout disc. A multi-micro cracks from compression straining are formed in the second stage, the main direction of these cracks running from top of disc to bottom of counter pressure ring forming a cone. The third stage of internal rupture occurs by forming a tensile/shear crack running from the outside edge of the disc to the inside edge of the counter pressure ring and forming the cone failure surface.

Petersen and Hansen (27) performed a study by using the Lok-Test and the Coma-Meter, they concluded that the developed system combining pullout testing and maturity measurements proved to be a reliable and economical solution to the problem of achieving sufficient knowledge of the in-situ strength when rapid construction schedule is of importance.

Johansen and Einar-Dahl (19) performed a study to evaluate the ability testing methods (Lok-Test and TNS test) to detect variation in concrete quality and curing conditions. They stated that Lok-Test demonstrates a better ability to differentiate between concrete qualities, and both tests can be used to test young concrete.

2.2 Types of pullout techniques

Pullout tests are divided into two basic categories: the first one has an insert which is cast into the concrete; the other has an insert fixed into a hole drilled into the hardened concrete. Some of these types are as follows:

2.2.1 Type 1 (Ref. 4):

The pullout inserts are machined from high tensile steel material. The inserts are held in the wooden moulds by tightening the nuts and washers on threaded shafts. The embedded head of the insert has a diameter of 25 mm and the distance between the inner surface of the embedded head and the inside of the formwork is kept constant at 25 mm. The embedded insert is pulled out of the hardened concrete by means of a loading system. The sequence of performing a pullout test is illustrated diagrammatically in Fig. 2.9 .

2.2.2 Type 2 (Ref. 2):

The pullout assembly consists of a threaded steel shaft 3/4 in (19mm) in diameter and 4.25 in. (107 mm) long together with a 2.25 in. (57mm)*1/8 in (2.8mm) thick washer which was to serve as the embedded head. The assembly is held in position in the formwork by nuts and washers as shown in Fig. 2.10a . The critical dimension are the diameter of the washer and the distance between the bottom of the washer and the inside of the formwork. This distance is kept constant at 2.08 in (52.8mm). The steel shaft and the embedded head are pulled out of the hardened concrete by means of a hollow tension ram which exerts pressure through a bearing ring with an inside diameter 5.0 in (127mm) and thickness 1/2 in (12.5mm). The inside diameter of the bearing ring, the outside diameter of the embedded head, and the distance between them control the size and the apex angle of the concrete cone that will be pulled out Fig. 2.10b . Great care should be taken to ensure that the height "h" is kept constant in each assembly. All threaded shafts, washers, and nuts are cleaned to ensure a satisfactory bond between steel and concrete.

2.2.3 Type 3 Tapered bolts (Ref. 6):

This type consisted of pulling out a tapered bolt that had been forced by means of a calibrated torque into a special threaded sleeve positioned in a drilled hole in the concrete Fig. 2.11 . The sleeve, which has an external diameter nearly equal to that of the drilled hole, consists of two semi-circular parts held together by rings and designed to fit the tapered bolt. The sleeve is first placed in the upper part of the hole, ensuring that there is no differential displacement between the two components. The tapered bolt is then screwed into the sleeve and the assembly carefully brought down the hole with a hammer. The bolt is subsequently removed and tension ram and its support are put in position for the test. The bolt is reinserted into the sleeve through the tension ram and again partly tightened till lightly retaining the whole assembly. The test is performed and recording the force required to pull it out with the ram simultaneously pulling out a section of the concrete.

2.2.4 Type (4) Epoxy grouted bolts (Ref. 6):

This technique consists of pulling out a bolt set in the hardened concrete with an epoxy. The method and the details of the equipment are illustrated in Fig. 2.12 . The drilled hole is carefully cleaned and dried to filling with a flowing epoxy. The bolt, a threaded steel rod, is placed into the epoxy with a slow rotary motion. During the initial stage of hardening of the epoxy, a support is needed to hold the bolt perpendicular to the surface of the slab. After proper curing of the epoxy, the bolt is pulled out using a tension ram assembly,with the load being applied uniformly till failure of the concrete occures.

2.2.5 Type (5) Lok-test (Ref. 7)

2.2.5.1 Development of Lok-Test:

The Danish Society of Chemical, Civil, Electrical and Mechanical Engineers appointed a working committee on concrete control in 1959. The task of the committee was to prepare proposals for bringing up to date the Code of Practice for the Structural Use of Concrete(15). The committee agreed that one of the fundamental problems of concrete control was that strength requirements were made to the concrete in the structure, while the control was carried out on cast test specimens. Only by measurements on the structure itself it would be possible to check that important factors such as the transport of the fresh concrete, casting, compaction and curing. Then the committee proposed a control method with the following characteristics: the method should have the character of a destructive method, and it must be cheap; the measurements must be easy to carry out and they should be made on the concrete in the structure.

In 1962, Kierkegaard-Hansen devised the method that is known today as Lok-Test. Its name is taken from the Danish word "Lokning". The first investigations were carried out in August 1962 in Dr. Anders Nielsen's laboratory. In 1963, work began on the development of special laboratory apparatus. From then until 1966, The Danish National Institute of Building Research carried out a large number of tests. From 1967 to 1968 the method was tested in practice. In 1969 the Danish Society of Civil Engineers requested the Department of Structural Engineering of the Techanical University of Denmark to carry out a number of control tests. Investigations made in 1969 to 1970 verified the correlation between the cylinder compression strength of the concrete and the lok strength.

Many investigations have been carried out to arrive at suitable dimensions for the test apparatus, where the diameter of the pullout disk, the depth of embedment and the diameter of the support ring were selected so as to obtain a linear relation between the pullout load and the corresponding independently measured uniaxial compressive strength (14).

2.2.5.2 Lok-Test Procedure:

The lok-test is a test where a solid part is extracted from the concrete by means of an embedded disk which is pulled out under application of a counterpressure.

The pull-out insert is a 25 mm diameter special steel disc held 25 mm from the testing surface by a removable shaft, which may be attached to the formwork using a circular hardboard plate nailed into place, or through the formwork using an adjustable screw Fig. 2.13a. It can also be placed in unformed surfaces of concrete using a floatation cup or steel plate.

During testing, all parts of the insert except the disc are removed Fig. 2.13b. A special pullbolt is threaded into the disc and attached to the testing instrument. A hand-powered hydraulic precision pulling machine, which has a 55 mm dia. counterpressure ring placed centrally on the testing surface Fig. 2.13c. Pulling force is applied by turning the instrument handle. The equipment automatically ensures correct centring and constant correct loading perpendicular to the testing surface.

A small cone between the disc and the counterpressure ring is released, and the pulling force is recorded. If the measurement indicates that the in-place strength of concrete is in excess of the specified strength, the test could be stopped without any visible damage to the structure. Alternatively, load may be applied untill compressive failure of the concrete and, if released immidately afterwards, only slight damage occurs to the concrete Fig. 2.13d. The instrument and the pulling bolt are removed, and the stem(the removable shaft) is reinserted in the disc leaving the surface almost untouched.

2.2.6 Type(6) Capo-test (Ref. 7):

The lok-test does not work when concrete strength of already built structure need to be found. For this purpose a special undercutting and subsequent expanding ring technique was developed. In this way the mechanism of failure would be the same as that of lok-test. It's name is derived from Cut And Pull-out test.

In this test, the reinforcement is located with a covermeter or a simple metal detector and the testing surface is ground smooth and flat with a heavy grinder in a 100 * 100 mm area. A hole is cut perpendicular to the surface with a special tool 18 mm in diameter, to a depth of 50 mm at least 20 mm from reinforcement position, and afterwards undercut with a diamond miller to a 25 mm hole positioned 25 mm from the concrete surface, to a depth of 10 mm.

An expanded insert is placed in the hole and is expanded with a special expansion unit Fig. 2.14b to ensure a correct circumferential connection between the expanded insert and the undercut groove surface. The unit and the insert are attached to a pullbolt, which is coupled to a lok-test instrument with a counterpressure ring placed on

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the testing surface and loaded. The CAPO strength is recorded as the maximum reading during pull-out, which in this case is always continued to past failure untill the cone of concrete is removed Fig. 2.14d. Since the Capo apparatus consists of several individual components it may require more assembly time and care.

Capo-test has been in use in Denmark on a number of sites. It takes approximately 10 minutes for one test provided the necessary electricity and water supply in present. The capo-inserts are reusable two or three times. The portable equipment, all kept in two small suitcases, makes it possible to carry out a large number of tests.

In order to get consistent data for pullout test, it is very important that the investigator understands the limitations of the test procedure and its application.

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AUTHOR (ref.; year of publishing)	CORRELATION NO	NUMBER AND TYPE OF REFERENCE SPECIMENS	NUMBER AND PLACEMENT OF PULLOUT TESTS	PARAMETER INVESTIGATED	CORRELATION: Pullout force P (kN), Cylinder strength f_c (MPa)	RANGE (MPa)	MAX AGGR SIZE (mm)	STANDARD DEVIATION AND COEFFICIENT OF VARIATION: Pullout force s (kN)	Pullout force v (%)	Cylinder strength s (MPa)	Cylinder strength v (%)	COEFFICIENT OF CORRELATION
GAY G (11) 1978	1	46 cylinders capped	46 on cylinder bottoms	curing time (c.t.)	$P_L = 0.905 \cdot f_c - 0.90$	15-130	18	0.5	9.[illegible]	[illegible]	2.3	0.91
BICKLEY J A (12) 1982	2	340 cylinders capped	340 on cylinder bottoms	age, w/c, aggr size, form source and c.t.	$P_L = 0.910 \cdot f_c - 0.32$	3.5-[illegible]	10 / 16, 38	2.0 / 3.1	4.[illegible] / 8.2	[illegible] / 2.7	1.9 / 7.6	0.96
KRENCHEL H (13) 1982	3	75 cylinders	52 on vertical faces of 200 mm cubes, two in each	age, w/c, aggr size and source, curing and air	$P_L = 0.874 \cdot f_c - 1.91$	3.3-33.0	16, 38	3.3	9.[illegible]	1.5	4.0	0.90
KRENCHEL H (13) 1982	4	75 cylinders	146 on vertical faces of 200 mm cubes, two in each	age, w/c, aggr size and source, curing and air	$P_C = 0.904 \cdot f_c - 0.52$	3.3-33.0	16, 38	3.3	9.[illegible]	1.6	4.5	0.93
KRENCHEL, H. (14) 1970	5	250 cylinders	500 on vertical faces of 200 mm cubes, two in each	age, w/c ratio and curing cond.	$P_L = 0.981 \cdot f_c - 0.53$	5.0-50.0	16, 32	3.6	15.2	1.1	3.3	0.93
JENSEN, J K J (15) 1978	6	96 cylinders	96 on one vertical face of 200 mm cubes	w/c ratio	$P_L = 0.520 \cdot f_c + 0.03$	5.0-50.0	16	2.9	9.5	2.6	6.4	0.96
DRAKE, K.D. (16) 1981-82	7	69 cylinders, 3 in each set, capped	184 on vertical faces of 200 mm cubes, eight in each set	c.t., w/c, aggr size, fly ash and additive	$P_L = 1.04 \cdot f_c - 0.94$	20-35.0	10, 16 & 22	1.7	7.7	0.5	1.8	0.99
DRAKE, K D (16) 1981	8	15 cylinders, 3 in each set, capped	20 on vertical faces of 200 mm cubes, four in ea.	curing time	$P_L = 0.68 \cdot f_c + 11.3$	30.0-74	22	N/A	N/A	N/A	N/A	0.99
POULSEN, P.E (17) 1975	9	36 columns (0.3x0.3x1m) IN-SITU	216 on vertical faces of another 36 columns	w/c ratio	$P_L = 0.831 \cdot f_c + 5.50$	10.0-30	16	2.7	11.[illegible]	2.1	5.6	0.96
KIERKEGAARD-HANSEN, P (18 and 19 p.-) 1975	10	100 cylinders	81 on cylinder bottoms	type of cement and aggr size	$P_L = 0.806 \cdot f_c - 5.10$	11.6-38.7	8, 16	1.8	6.0	1.8	3.6	0.99
LEKSOE, S (20) 1976	11	240 cylinders	360 on panel bottoms	w/c ratio, aggr size	$P_L = 0.800 \cdot f_c + 3.92$	20.0-55.0	25, 32	3.7	11.3	2.4	5.4	0.93
LEKSOE, S. (20) 1976	12	240 cylinders IN-SITU	360 on 30 structures, placed at random	w/c ratio, aggr size	$P_L = 0.710 \cdot f_c + 7.30$	20.0-55.0	25, 32	4.9	16.4	2.4	5.4	0.91
KRENCHEL, H (21) 1982	13	116 cylinders	216 on vertical faces of 200 mm cubes, two in ea.	age, w/c, aggr size and source, curing, air and admixt	$P_L = 0.758 \cdot f_c - 4.[illegible]0$	15.0-75.0	8, 16 and 32	2.2	2.9	1.1	3.6	0.95
KRENCHEL, H (21) 1982	14	116 cylinders	214 on vertical faces of 200 mm cubes, two in ea.	age, w/c, aggr size and source, curing, air and admixt	$P_C = 0.731 \cdot f_c - 3.30$	15.0-75.0	8, 16 and 32	2.1	7.8	1.1	3.6	0.95
MAGEE, R L (22) 1982	15	36 cylinders, capped	42 total, 18 on cylinder bottoms and 24 on vertical faces (4) of 200 mm cubes	curing time and w/c ratio	$P_L = 1.050 \cdot f_c + 1.00$	6.3-34.5	18	2.5	8.7	1.7	6.2	0.96
BICKLEY, J A (23) 1984	16	472 cylinders capped	472 on cylinder bottoms	age, w/c, aggr size, form source and c.t.	$P_L = 0.752 \cdot f_c - 3.53$	2.9-44.6	19	2.6	9.2	2.7	36	0.92

P_L Pullout force as measured with Lok-Test, P_C Pullout force as measured with Capo-Test

Table 2.1
Correlation data for sixteen calibrations relating pullout force to standard cylinder compression strength, Ref. (8)

AUTHOR (ref) year of publishing	CORRELATION NO	NUMBER AND TYPE OF REFERENCE SPECIMENS	NUMBER AND PLACEMENT OF PULLOUT TESTS	PARAMETER INVESTIGATED	CORRELATION Pullout force P (kN) – Cube-strength f'_c (MPa)	RANGE (MPa)	MAX. AGGR SIZE (mm)	STANDARD DEVIATION AND COEFFICIENT OF VARIATION: Pullout force s (kN)	Pullout force v (%)	Cube strength s (MPa)	Cube strength v (%)	COEFFICIENT OF CORRELATION
JOHANSEN, R (24) 1979	17	65 cores/cubes	65 on topport of panels (floating inserts, type L-49)	w/c-ratio, curing cond.	$P_L = 0.780 \cdot f'_c + 1.70$	8.0-35.0	16	2.4	9.5	1.5	5.0	0.94
GELHARD, R (25) 1979	18	140 cubes	140 on vertical face of 150 mm cubes (low range) and 200 mm cubes (high strength)	curing time	$P_L = 0.813 \cdot f'_c + 2.00$	12.0-64.0	32	3.3	8.0	3.2	6.6	0.95
van der WINDEN, N. (25) 1979	19	75 cubes	75 on vertical face of 150 mm cubes	w/c, curing time	$P_L = 0.792 \cdot f'_c + 1.50$	3.0-48.0	16,32	3.5	8.5	3.4	8.0	0.95
van der WINDEN, N (26) 1980	20	90 cubes	45 on vertical face of 150 mm cubes	curing time	$P_L = 0.758 \cdot f'_c + 2.23$	18.0-50.0	16	1.4	5.0	3.0	7.5	0.99
BELLANDER, U (27) 1979	21	420 cores, 20 in each panel and 180 job cubes, IN-SITU	378 on faces of vertical cast panels in-situ, 18 in each	type of cement, age, curing time and condit., compac, freezing	$P_L = 0.746 \cdot f'_c + 2.76$	10.0-60.0	16,38	4.7	11.0	6.0	13.5	N/A
BELLANDER, U (27) 1979	22	340 cores 20 in each panel	612 on faces of vertical cast panels in lab., 18 in each	type of cement, age, curing time	$P_L = 0.725 \cdot f'_c + 3.31$	10.0-60.0	16,38	2.6	6.3	1.6	6.0	N/A
BELLANDER, U (28) 1983	23	75 cubes, 3 in each set	75 on vertical face of 150 mm cube, 3 in each set	w/c-ratio, aggr. size	$P_L = 0.705 \cdot f'_c + 1.80$ *)	3.0-85.0	16,38	2.0	5.0	2.0	5.0	0.98
BELLANDER, U (28) 1983	24	75 cubes, 3 in each set	75 on vertical face of 150 mm cube, 3 in each set	w/c-ratio, aggr. size	$P_C = 0.696 \cdot f'_c + 1.68$ *)	3.0-85.0	16,38	2.0	5.5	2.0	5.0	0.98

*) Slope corrected 10% due to radial cracking as outlined in ref 10.
P_L Pullout force as measured with Lok-Test, P_C: Pullout force as measured with Capo-Test

Table 2.2
Correlation data for eight calibrations relating pullout force to standard cube compressive strength, Ref. (8)

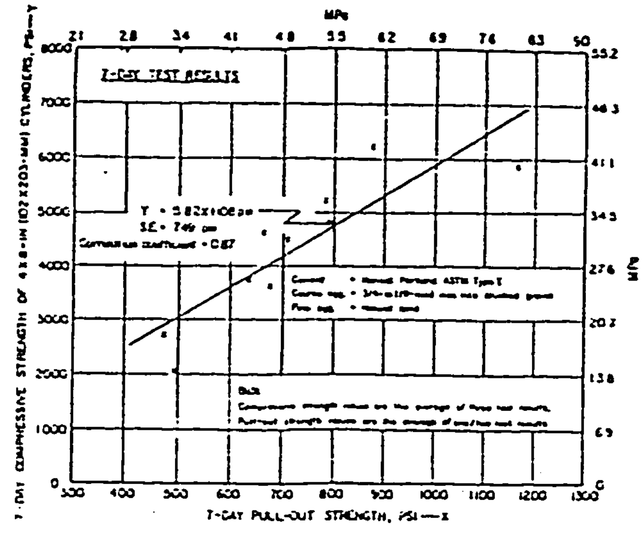


Fig.2-1 a Relationship between pullout and 7-day compressive strength of 4 x 8-in. (102 x 203-mm) cylinders

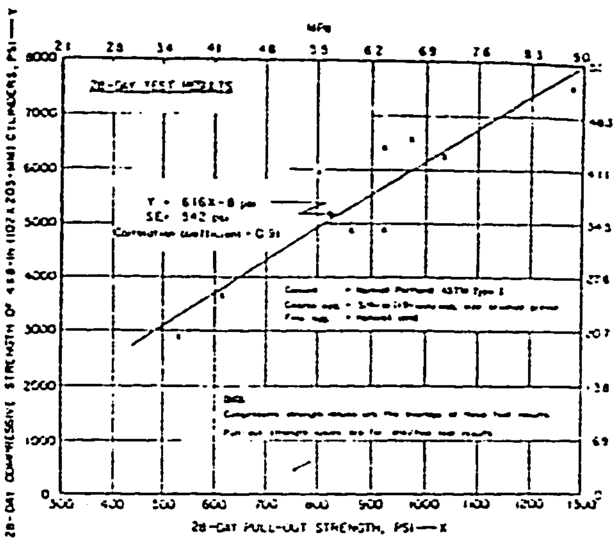


Fig. 2-1b Relationship between pullout and 28-day compressive strength of 4 x 8-in. (102 x 203-mm) cylinders

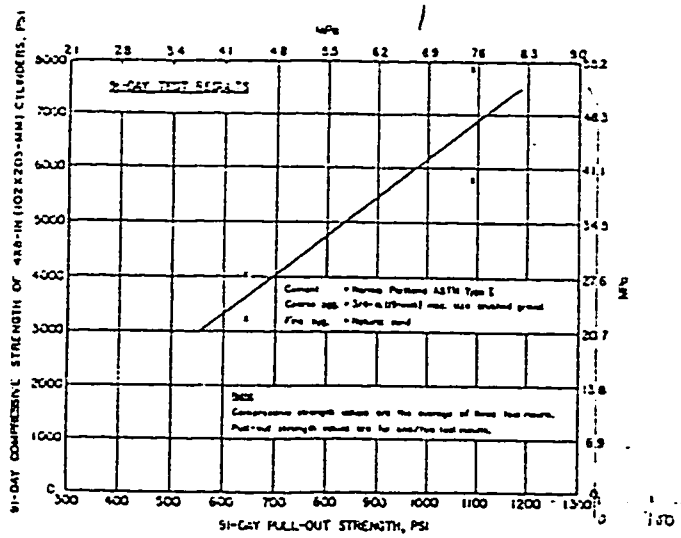


Fig.2-1 c Relationship between pullout and 91-day compressive strength of 4 x 8-in. (102 x 203-mm) cylinders

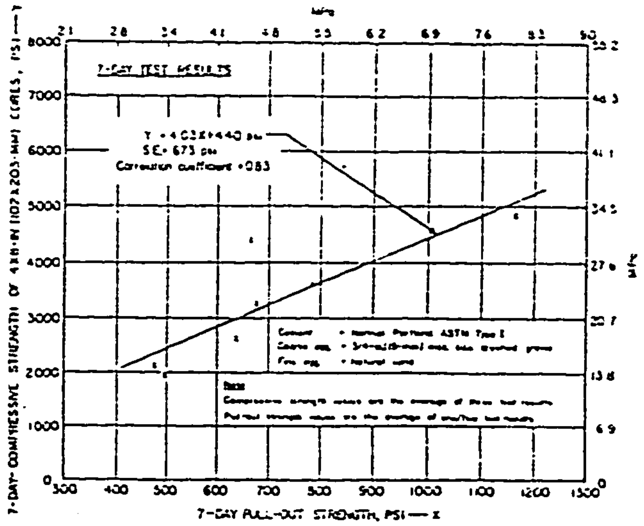


Fig.2-2 a Relationship between pullout and compressive strength of 4 x 8-in. (102 x 203-mm) cores drilled after 7 days

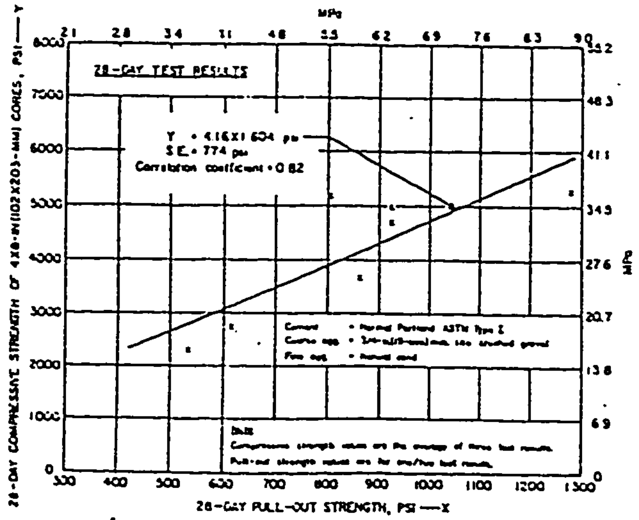


Fig.2-2 b. Relationship between pullout and compressive strength of 4 x 8-in. (102 x 203-mm) cores drilled after 28 days

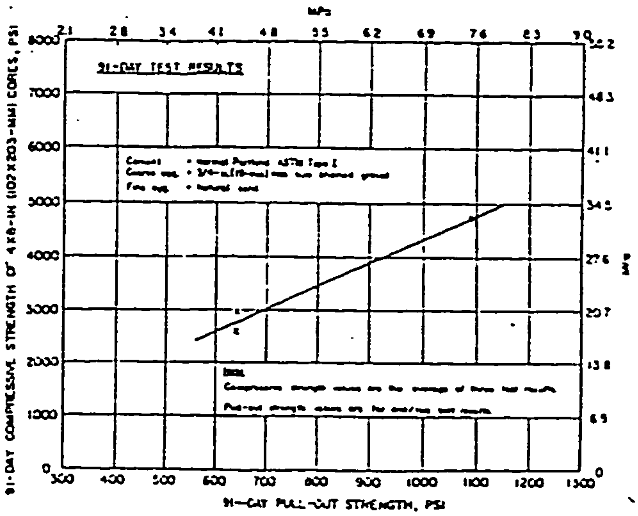


Fig.2-2 c. Relationship between pullout and compressive strength of 4 x 8-in. (102 x 203-mm) cores drilled after 91 days

Ref.(2)

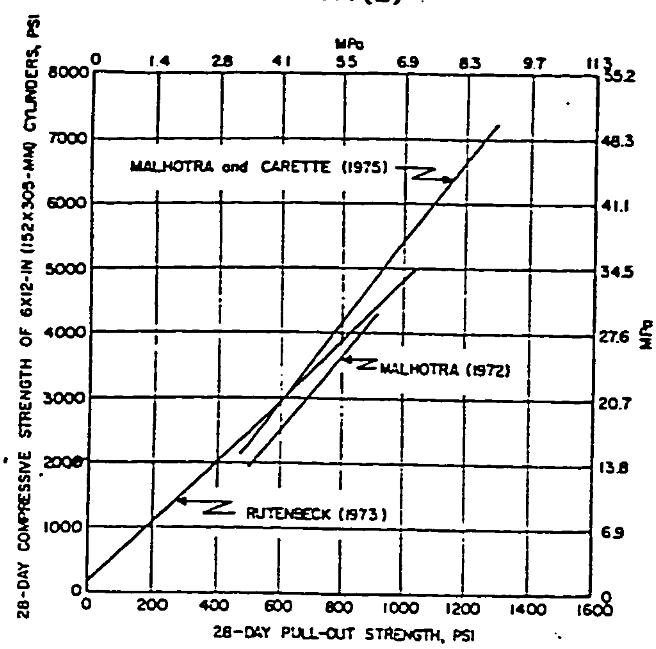


Fig. 2.3 Comparison of relationships obtained in this investigation with those obtained by others

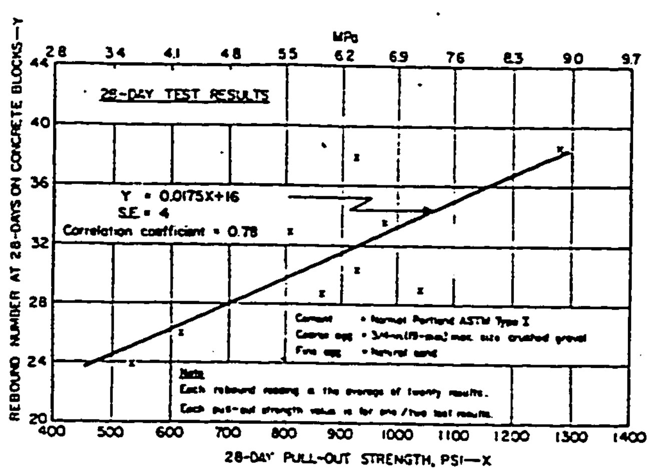


Fig. 2.4 Relationship between pullout strength and rebound number of 28 days

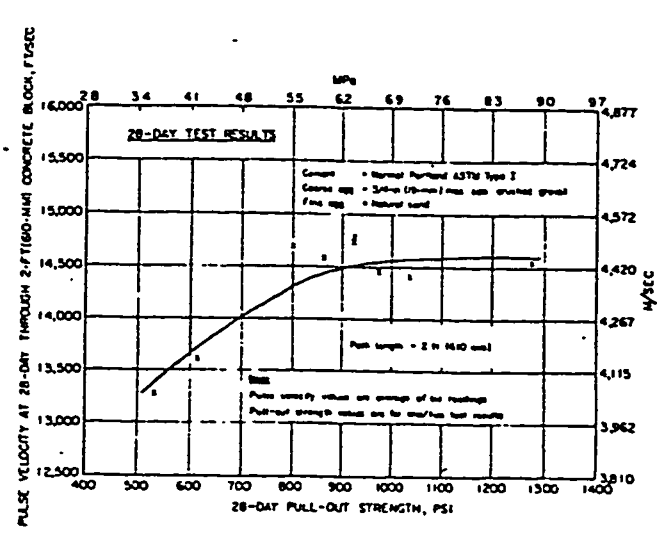


Fig. 2.5 Relationship between pullout strength and pulse velocity at 28 days

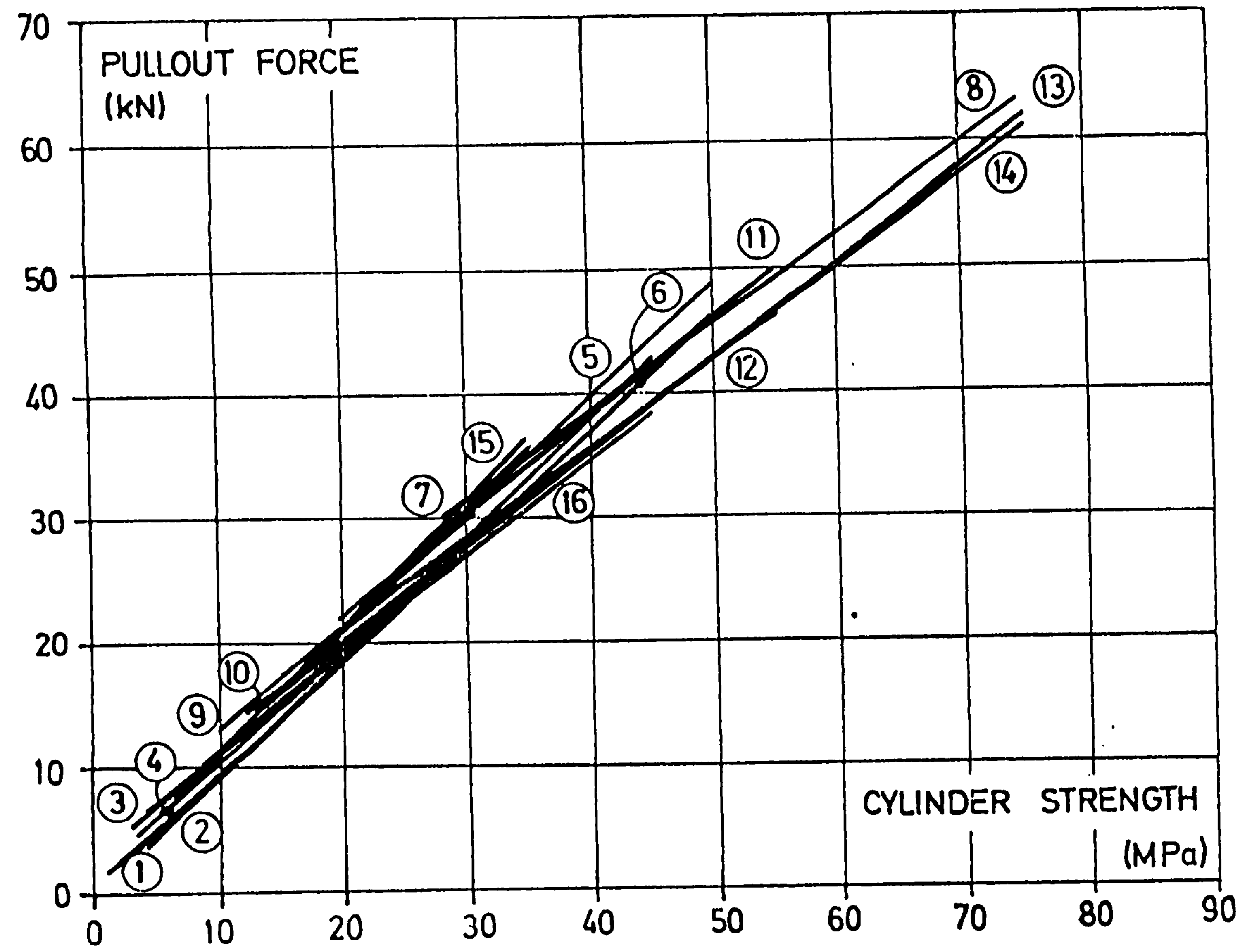


Figure 2.6a
Sixteen correlations between pullout force and standard cylinder compression strength, Ref. (8)

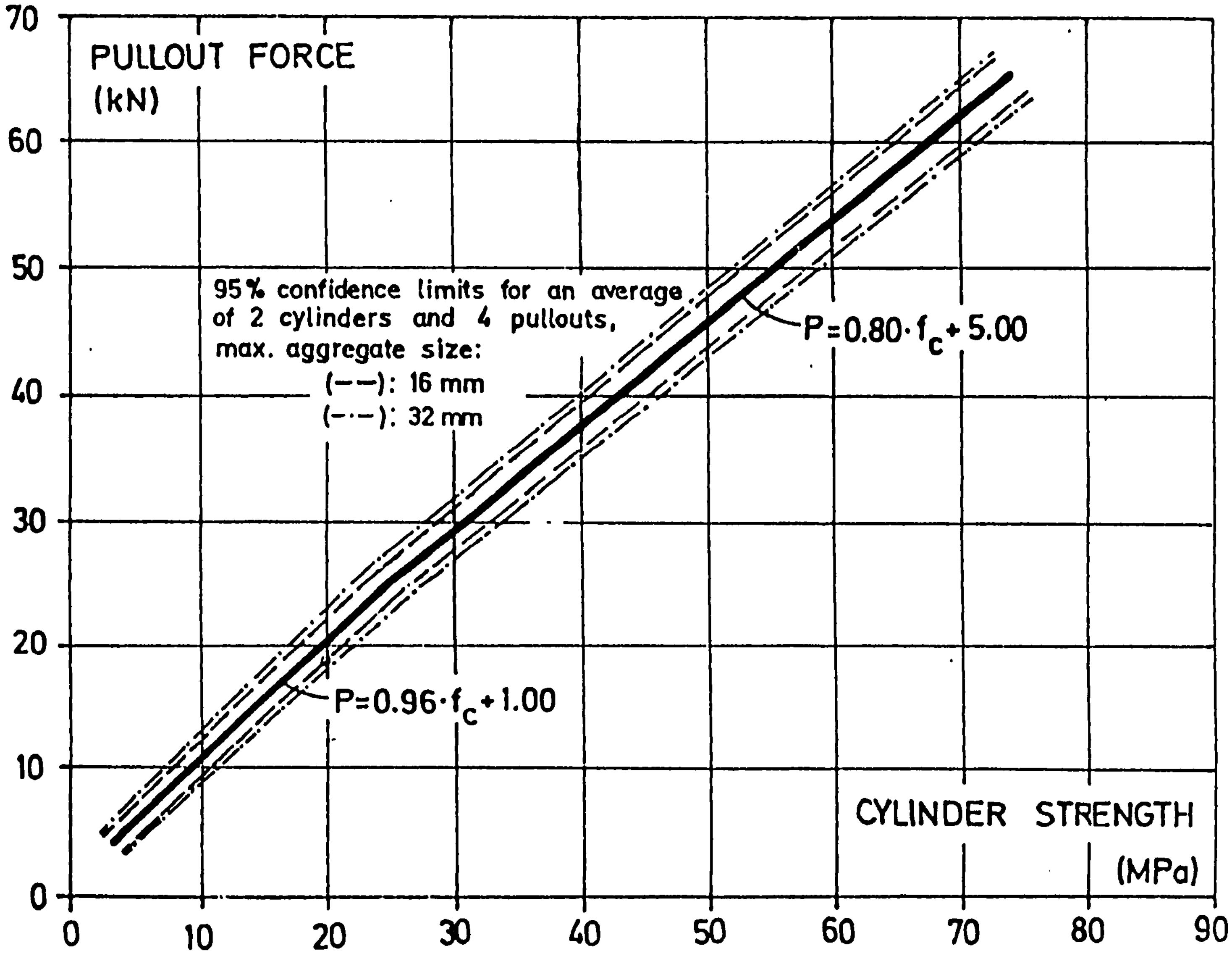


Figure 2.6b
Recommended correlation between pullout force and standard cylinder compression strength, *Ref.(8)*

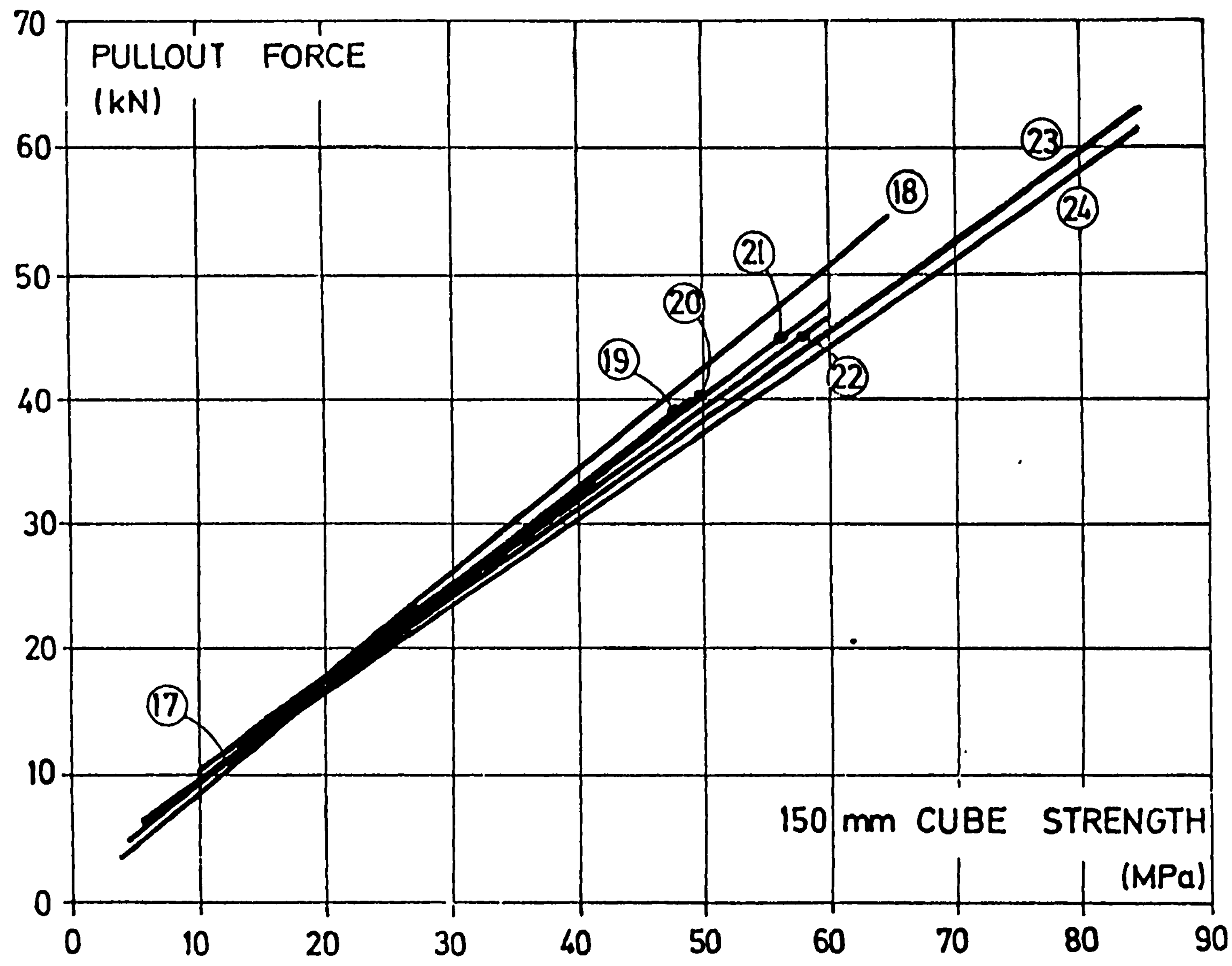


Figure 2.7a
Eight correlations between pullout force
and standard cube compression strength, Ref. (8)

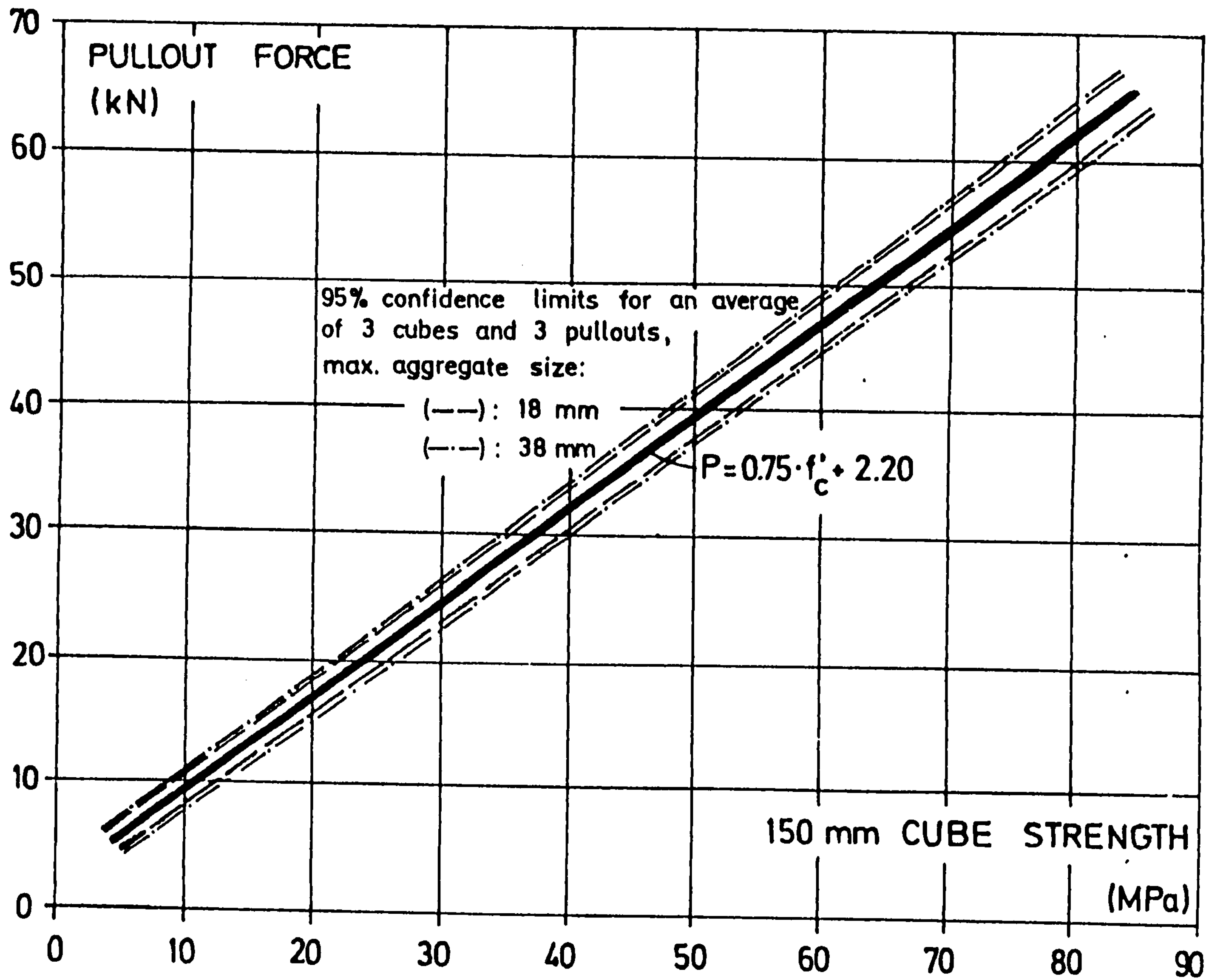


Figure 2.7b
Recommended correlation between pullout force and standard cube compression strength, Ref.(8)

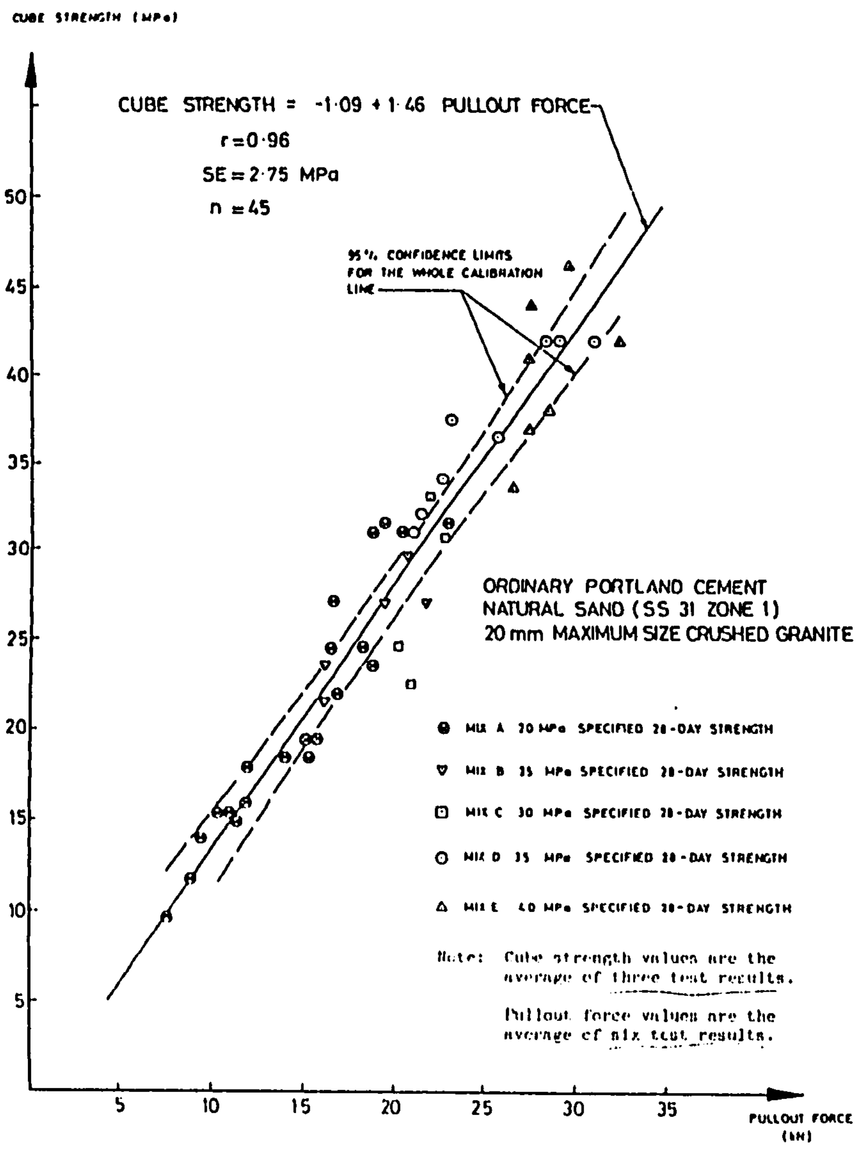


Fig.2.8a Relationship between cube strength (150-mm) and pullout force Ref. (4)

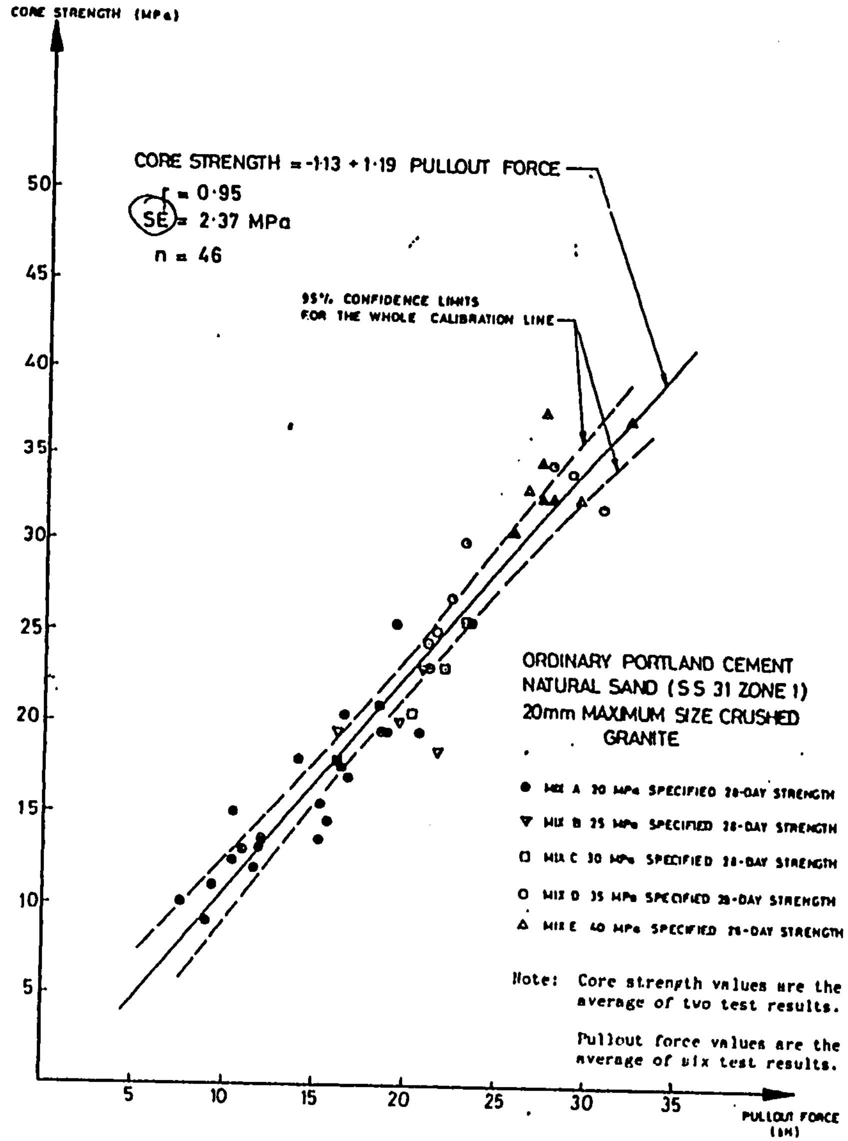


Fig.2.8b Relationship between core strength (ϕ100 x 200-mm) and pullout force Ref. (4)

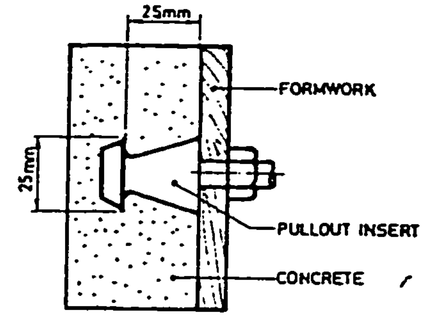


Fig a The machined pullout insert is mounted on the inside of the form prior to placing concrete

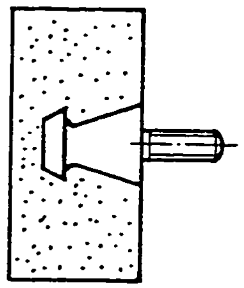


Fig. b The formwork (or part of the formwork) is removed

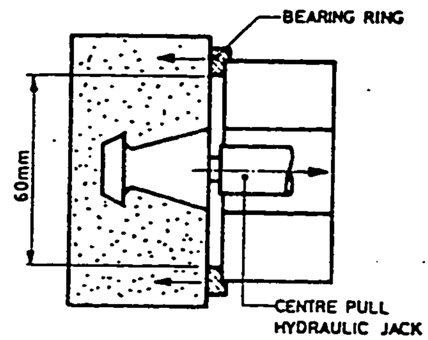


Fig. c The centre pull hydraulic jack with a 60-mm internal diameter bearing ring is mounted on the surface of concrete

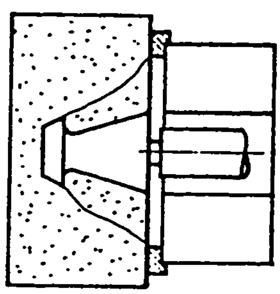


Fig. d A force is gradually applied on the insert and a small piece of the concrete is dislodged. The force required to pullout the insert through the counter pressure device (bearing ring) is called the pullout force.

Fig. 2.9 Ref. (4)

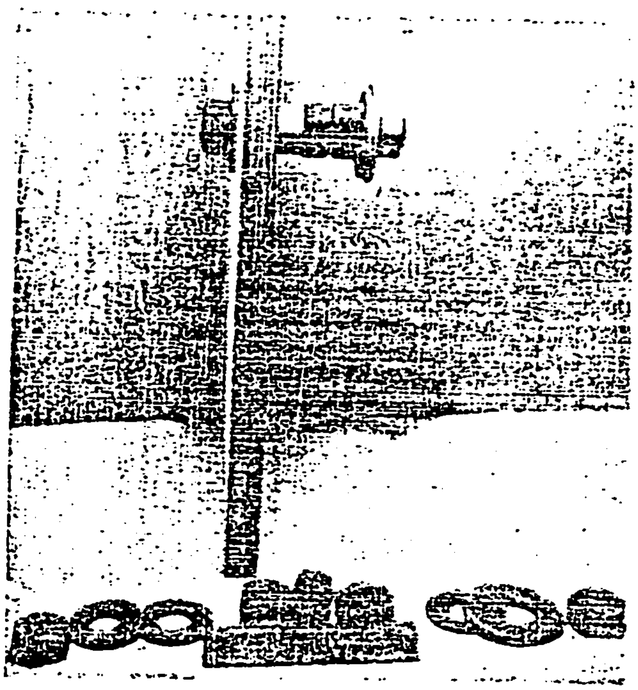
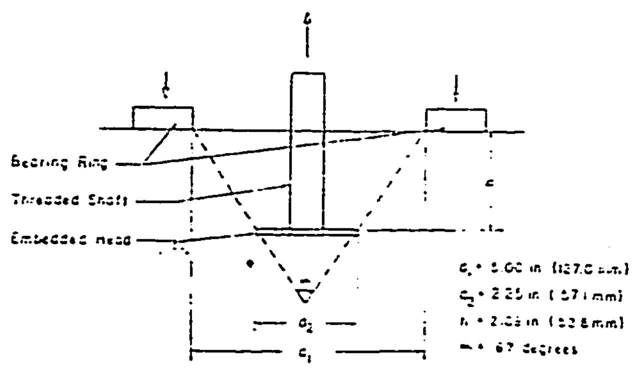


Fig.2-10a Pullout assembly with plywood form (exploded view at bottom). The diameter of the threaded shaft is ¾ in. (19 mm)



Note 1: Experience indicates that the above dimensions are most suitable.

Note 2: Total area A of convex surface of a frustum of a right circular cone is equal to, i.e.

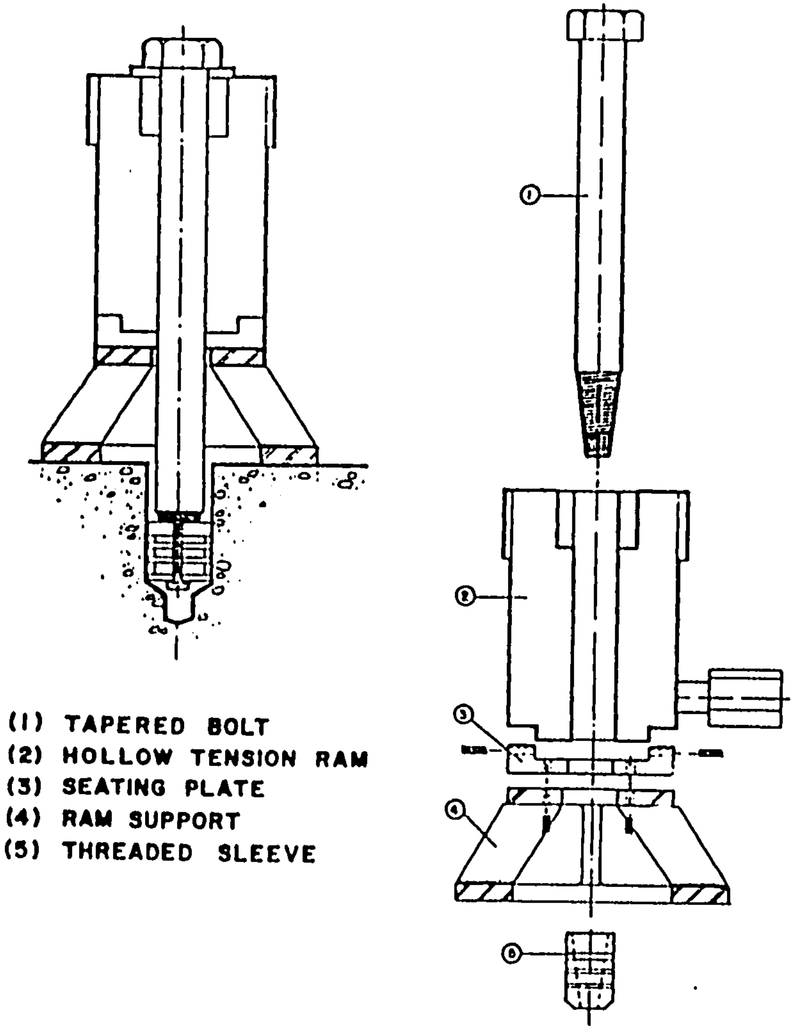
$$A = \pi s(d_1/2 + d_2/2)$$

where $s = \sqrt{h^2 + (d_1/2 - d_2/2)^2}$

substituting for s, d_1 and d_2, we get:

$$A = 28.40 \text{ in.}^2 \ (181.6 \text{ cm}^2)$$

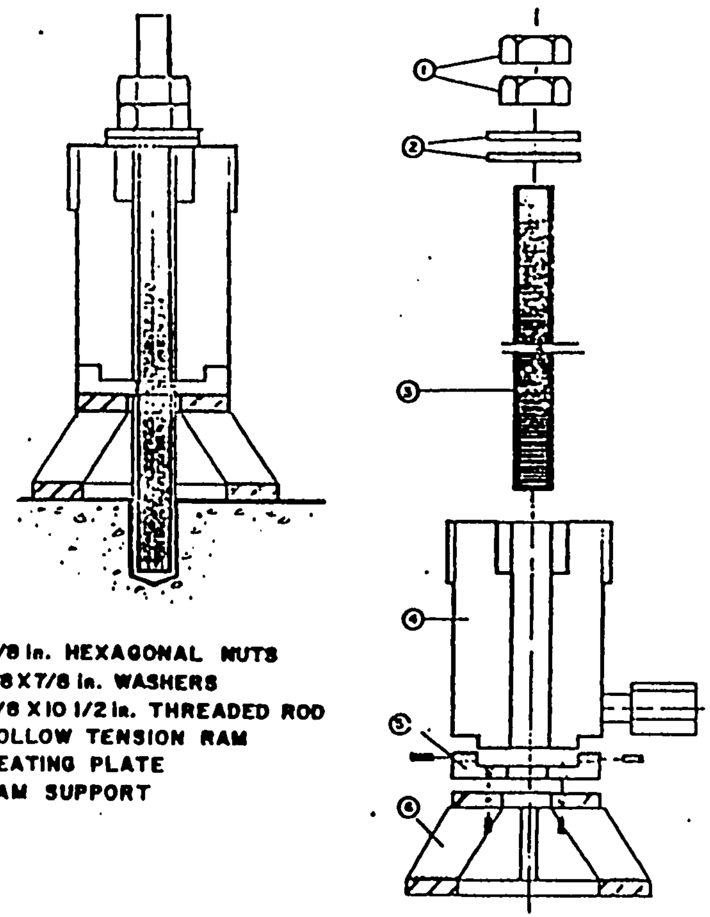
Fig.2.10b Sketch showing position and dimensions of the bearing plate, threaded shaft, and the embedded head, Ref.(2)



(1) TAPERED BOLT
(2) HOLLOW TENSION RAM
(3) SEATING PLATE
(4) RAM SUPPORT
(5) THREADED SLEEVE

Fig.2.11 General arrangement of tapered bolt pullout assembly

Ref.(6)



(1) 5/8 in. HEXAGONAL NUTS
(2) 1/8 X 7/8 in. WASHERS
(3) 5/8 X 10 1/2 in. THREADED ROD
(4) HOLLOW TENSION RAM
(5) SEATING PLATE
(6) RAM SUPPORT

Fig. 2.12 view of pullout assembly for epoxy grouted bolts

Ref. (6)

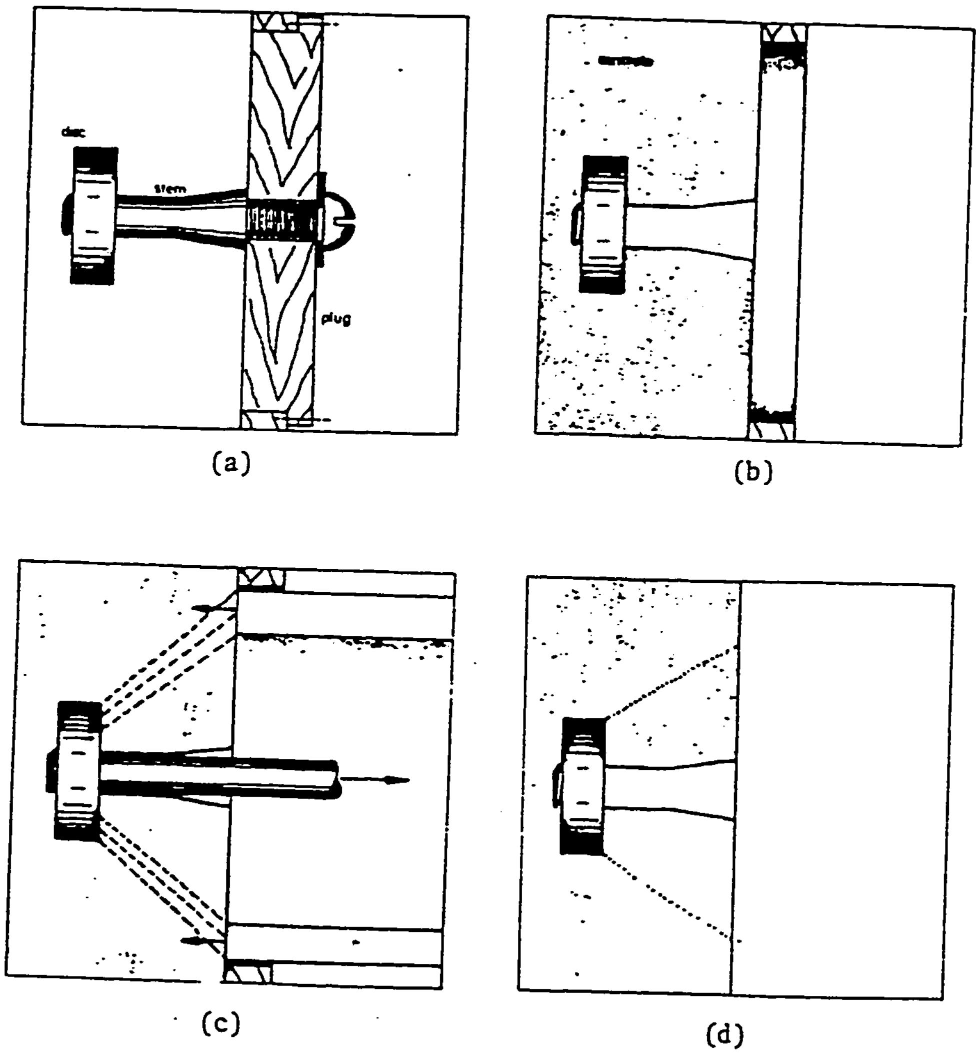


Fig. 2·13 Lok-test procedure for early stripping of formwork Ref.(7)

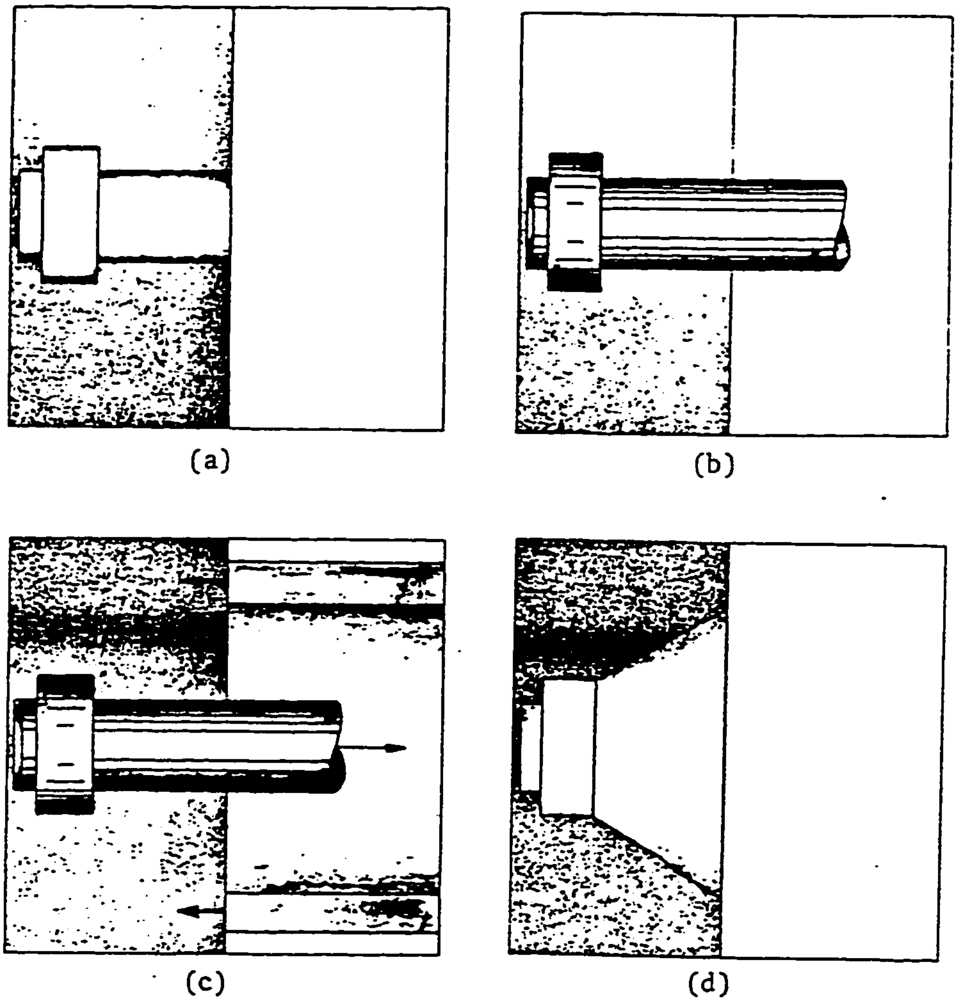


Fig. 2-14 Capo-test procedure for testing hardened concrete
Ref. (7)

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 General

An elaborate test program is designed to generate sufficient amount of test data which would serve as the basis of the development of the strength prediction models using Lok-Test and Capo-Test.

To examine the effect of various variable parameters, such as cement content, water-cement ratio and type of aggregate, so as to observe the influence of each of these variables on the strength.

3.2 Scope of investigation

In this study, the water-cement ratio is varied from .45 to .70 and corresponding cement content varied from 300 to 400 kg/ m^3. for each mix, two concrete panels of 750 * 500 * 150 mm and twenty one 75 * 150 mm cylinders are cast. These cylinders are tested in direct compression for evaluation of 3,7,14,28 and 91 days compressive strength. The Lok-Test on the concrete panels are made at 3,7,14 and 28 days. Also, the panels are subjected to Capo-Tests at 14,28 and 91 days. In addition, 75 * 150 mm cores were drilled from the panels at 7,14,28 and 91 days,

Tables 3.1 and 3.2 show the gradation of coarse and fine aggregates used in mixes, Fig. 3.1 shows the experimental program procedure. The water content was adjusted according to the moisture content and the absorption capacity of the aggregates.

3.3 Materials and molds:

Two types of aggregates were used in this study, the first one is crushed limestone from Jabel Dhahran area and the other is from Abu-Hadriyah, which are commonly used in The Eastern Province.

The aggregate used were unwashed and its water absorption had been taken in consideration during the design of mixes. For mixes having low water cement ratios, superplasticizers were used to get the desired workability. The nominal maximum size of coarse aggregate used was limited to 20 mm (3/4").

The fine aggregate used was Abqiq-Road sand, the cement was Type V. Portable tap water was used in mixing and curing of all concrete specimens.

Two types of molds were used in this experimental study, wooden molds for repeatitive use with inside dimensions
of 1500 * 750 * 150 mm to get two slab panels of 750 * 500 * 150 mm, and plastic molds for standard cylinders. For each wooden mold 14 inserts of Lok-Test had been fixed before casting as shown in Plate 3.1. The concrete cylinders were tested for compressive strength, and the panels were used to perform Lok and Capo tests and cores strength.

3.4 Casting and curing of specimens:

By using concrete mixer the coarse and fine aggregates and cement were mixed dry , measured amounts of sweet water was added and the constituents were mixed together.

The molds were cast by filling the forms progressively from one end, the compacting was done by using an electrical internal vibrator. For each mix the 21 (75 * 150 mm) cylinders were cast by filling the plastic molds in approximately three equal layers and compacting on a vibrating table. After casting all the

the molded specimens were covered with plastic sheets or burlaps, left in the casting place for 24 to 48 hours and then demolded and transferred to the curing and testing place. All the specimens were moist cured for 7 days followed by curing in air.

3.5 Test Procedure:

3.5.1 Compressive Strength Test:

Compressive strength was determined by testing 75 * 150 mm standard cylinders on a compression testing machine. The test method simply consisted of applying compressive axial load to cylinders until failure occured. The compressive strength of the specimen is calculated by dividing the maximum load attained by the cross-sectional area of the specimen. All the tested cylinders were first capped with sulphur before testing.

3.5.2 Core samples:

For the purpose of comparison of the cylinder strength versus the in-situ strength of the panels of identical mix design, cores taken from the panels by using coring machine Plate 3.2, and the water was supplied continuously during the coring process. Concrete panels were drilled vertically through the thickness of the panels. Each core was of 75 * 150 mm dimensions, the cores were capped and tested.

3.5.3 Lok-Test:

From each mix, two concrete panels were cast on which 14 lok inserts were fixed. Each panel has 7 inserts distributed at equal distances in the middle of thickness on two sides as shown in Plate 3.3. At the age of testing 3, 7, 14, and 28 days three lok tests have been performed, as the following procedure :

(1) The Lok-Test inserts are placed in the form before casting of concrete see Plate 3.4 . The distance between disc and form surface is 25 mm.

(2) After one or two days of casting, the screw removed and the form demolded.

(3) At the time of testing, using the stem handle turn the stem out of the concrete and remove it from the stem handle with a plier as shown in Plate 3.5 .

(4) A special pullbolt is pushed through the coupling and the centering plate, where the coupling curved inner surface should face the curved surface of the pullbolt. Using the bolt handle, turn the pullbolt in anticlockwise direction, untill the disc in the concrete is completely threaded on as shown in Plate 3.6. If the coupling is free to rotate , back off the pullbolt 1/2

rotation, Plate 3.7 shows parts of the assembly.

(5) The handle of the Lok -test instrument should be turned anti-clockwise untill fully extended. The instrument attached to the coupling by turning the coupling and sliding the heads of the three bolts, Plate 3.8, through the wide sections of the elongated holes in the coupling. The instrument put against the surface and twist the coupling anti-clockwise by inserting finger and thumb through the portholes in the instrument front part, to lock it on to the instrument bolt head, Plate 3.9 illustrates this step.

(6) The handle of the telescope was turned clockwise, so the loading will take place. At the moment of failure of concrete the pointer of the guage will stop moving and fall back, and the pulling force was recorded. Plate 3.10 shows the hydraulic pulling machine. however, excessive twisting may cause leakage of oil, to avoid that it is recommended to turn the handle slowly.

(7) Remove the instrument from the coupling by turning the coupling clockwise, then remove the pullbolt assembly by turning the pullbolt clockwise with bolt handle. in this case, the surface of the concrete will be left without any damage as shown in Plate 3.11. If the load

continued untill failure, there will be a hole in the concrete measuring 25 mm in depth and 55 mm in diameter see Plate 3.12. The remaining part of the structure will be undamaged.

3.5.4 Capo-Test:

Capo tests conducted three times at age 14, 28, and 91 days on the two remaining sides of the concrete panels, Plate 3.13 shows the tools of this test. The procedure of test is as the following :

(1) An area of 100 mm * 100 mm of the concrete surface was cleaned and made plane and smooth by using a heavy grinder.

(2) The top part of the rubber coupling was connected to the drill machine and tighten. One of the plastic hoses was attached to the drill housing nipple closest to the drill machine to supply water about 2 liters is required per test. Attaching a second hose to the bottom nipple to eliminate dirty waste water.

(3) A hole of 18 mm in diameter and 45 mm in depth perpendicular to the concrete surface was prepared using the drill machine, the core should be broken and removed by using the tweezers as shown in Plate 3.14.

(4) Using the milling cutter unit with its diamond miller make a groove into the hole with 25 mm diameter, positioned 25 mm from the concrete surface and 10 mm in depth as shown in Plate 3.15 and 3.16.

(5) The assembly expansion unit is shown in Plate 3.17, the Capo-insert is placed on the pullbar with cone. The press part was placed on the pullbar and thread the pullbar into the base pullbolt fully and thread the nut on the base pullbolt.

(6) The expansion unit inserted into the hole. If needed, push the tool in position by placing a wooden block on the end of the base pullbolt. Otherwise, enlarge the hole diameter by using the diamond drill. The press plate must be flush with the concrete surface with no space in between.

(7) The insert should be expanded to fill the groove as shown in Plate 3.18. The nut was turned with the large 45 mm key in a clockwise direction while holding the base pullbolt steady with the adjustable key. The Capo insert is expanded as the pullbar with cone is forced into it. The expansion of the insert is complete when the thread on the base pullbolt appears on the upper surface of the nut.

(8) The counterpressure ring was put over the expansion unit where the flat face towards the concrete and fix the coupling on the base pullbolt. connect this assembly to the Lok-Test instrument and turn the handle slowly untill the failure cone is taken out of concret as shown in Plate 3.19.

(9) After the failure cone extracted Plate 3.20, turn the coupling clockwise and lift the expansion unit with the counterpressure ring away from the instrument. Remove the coupling and counterpressure from the assembly, release Capo cone and the insert if not broken.

Table 3.1: Gradation of Coarse Aggregate

Sieve no.	% Passing	% Ret.
1"	100	0.0
3/4"	90	10.0
3/8"	20	80.0
3/16"	0.0	100.0

CA/FA = 1.63

Max. aggregate size= 3/4"

Type of test

LOK-TEST | CAPO-TEST | CORES | CYLINDERS

Age of test

3,7,14,28 | 14,28,91 | 7,14,28,91 | 3,7,14,28,91

W/C ratios

0.45 | 0.55 | 0.65

Cement contents

300 | 400

Type of aggregate

Jabel Dhahran | Abu-Hadriyah

Fig. 3.1 chart of the experimental program

SIEVE ANALYSIS						
SIEVE #	WT. OF EMPTY PAN (g)	WT. OF PAN + SAND (g)	WT. OF SAND		CUMULATIVE %	
			(g)	RETAIN %	RETAIN	PASS
3/8						
4						
8						100.00
16	414.4	414.7	0.3	0.03	0.03	99.97
30	403.3	457.5	54.2	5.42	5.45	94.55
50	380.7	916.2	535.5	53.55	59.0	41.00
100	356.8	624.7	267.9	26.79	85.79	14.21
200	294.1	432.0	137.9	13.79	99.58	0.42
PAN	250.2	284.0	3.60	0.38	99.96	0.04
TOT.			999.6			
WT. OF SAMPLE: 1000.0 gms						

Table 3.2 The gradation of fine aggregate

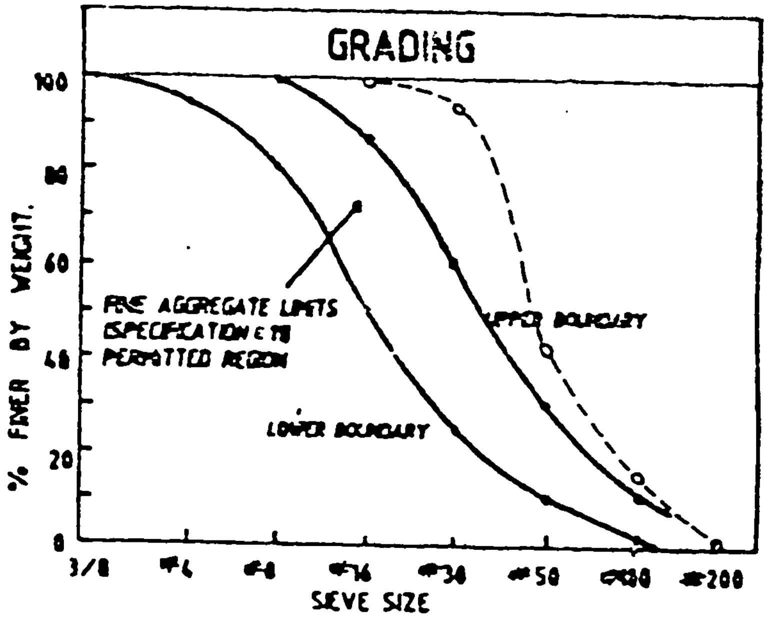


Fig. 3.2 The gradation of fine aggregate

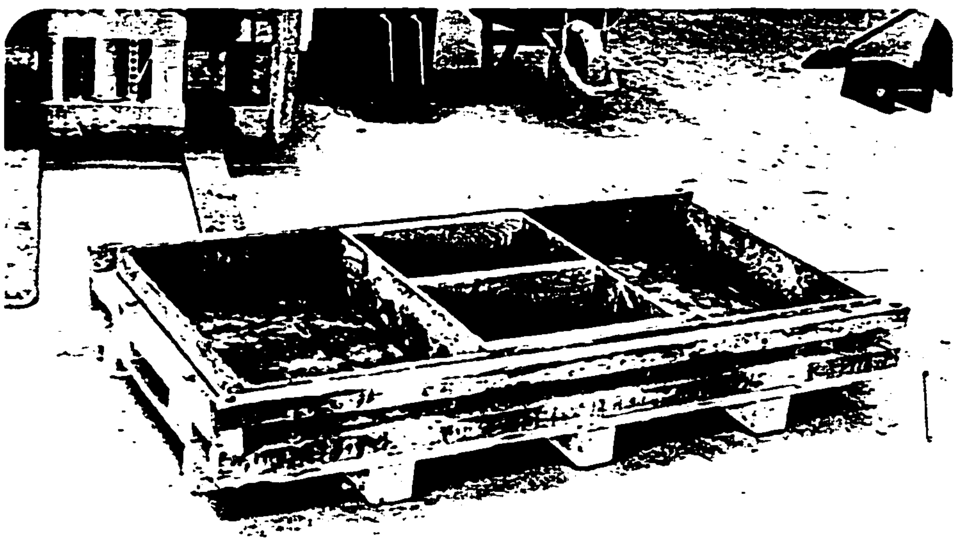


Plate 3.1 Wooden mold for casting panels.

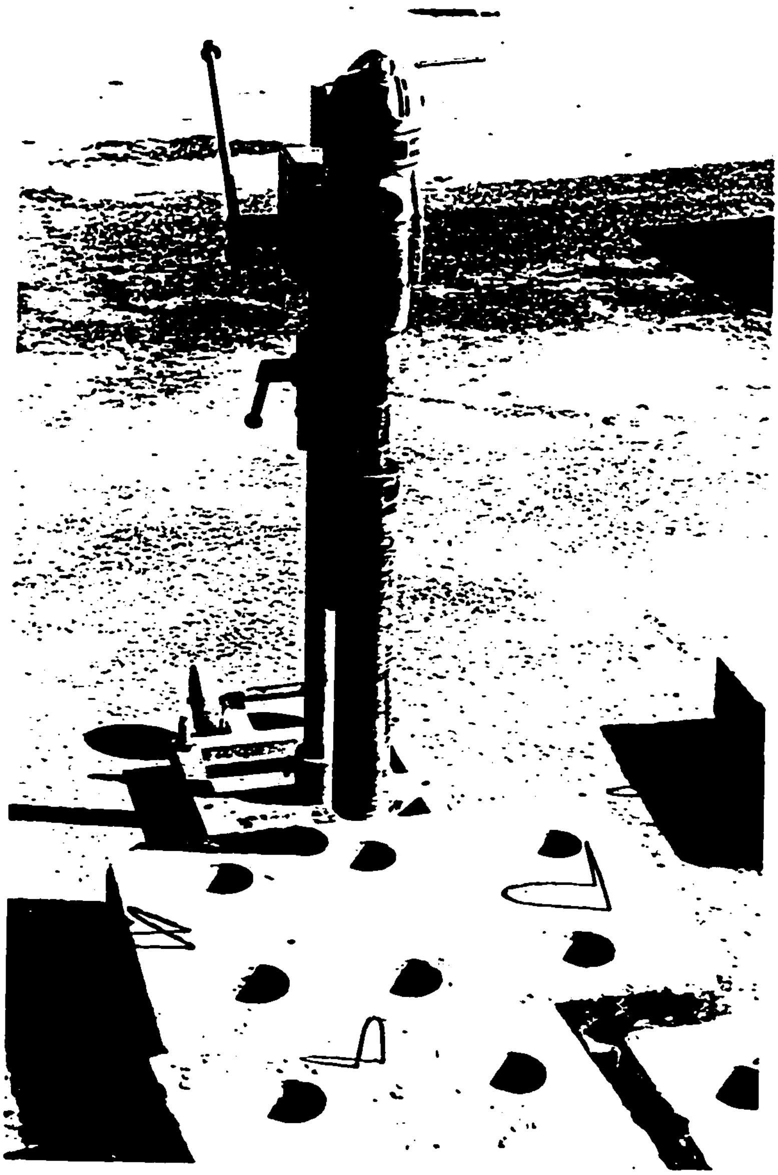


Plate 3.2 Coring machine.

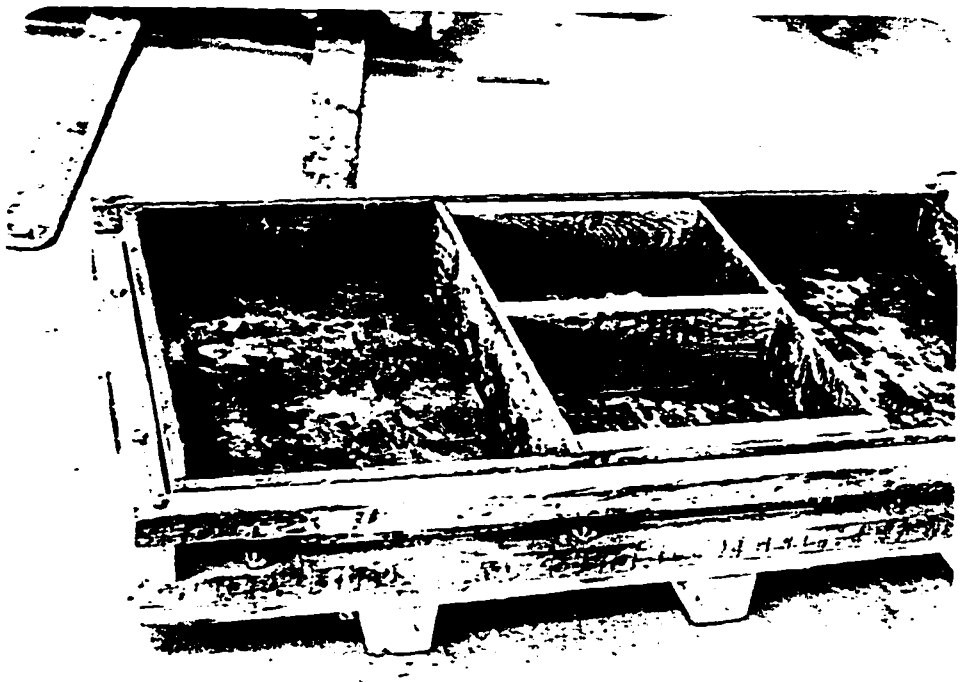


Plate 3.3 Lok inserts are fixed before casting.

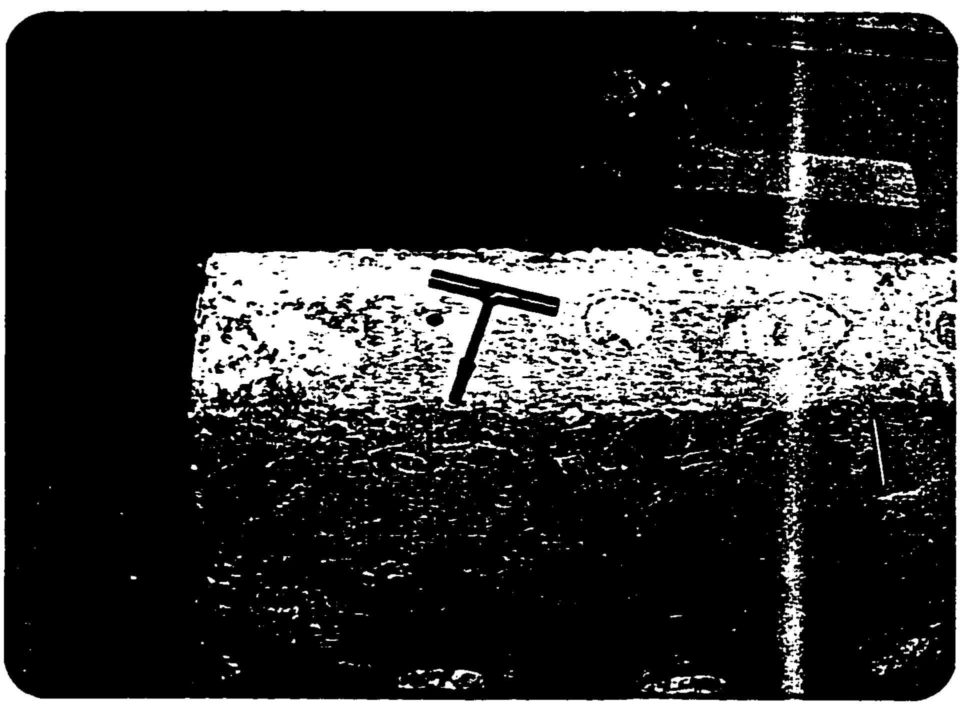


Plate 3.4 Position of Lok inserts on panel.

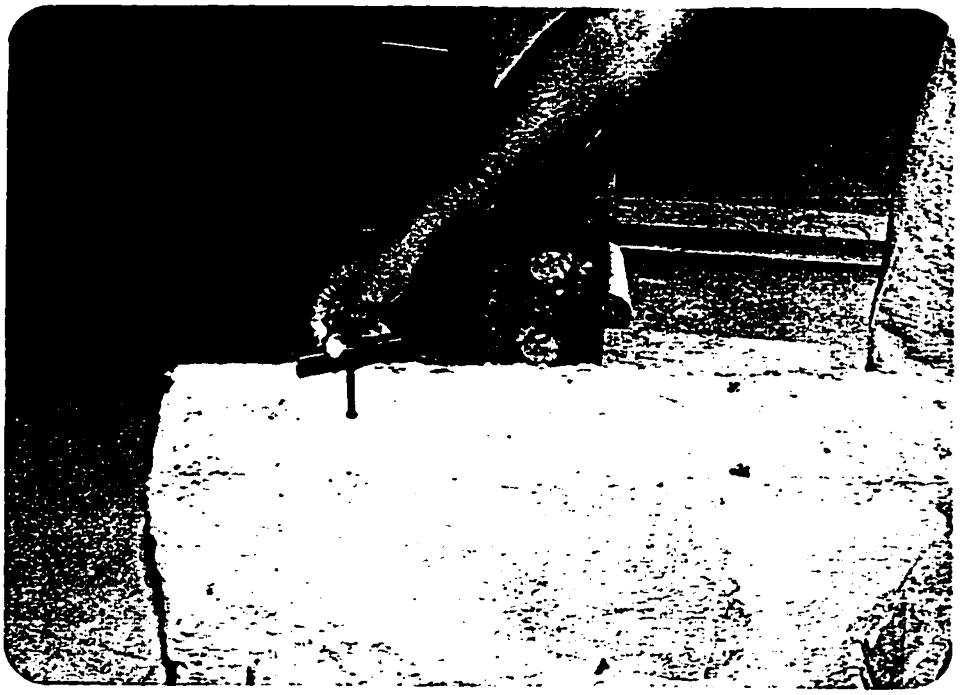


Plate 3.5 Stem handle turning stem out of the concrete.

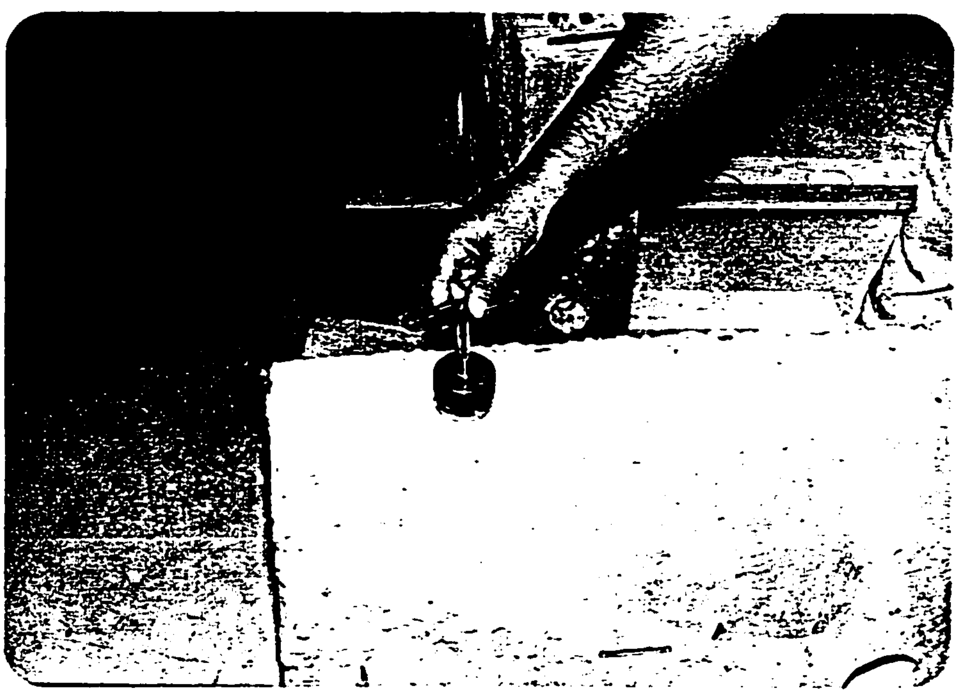


Plate 3.6 Bolt handle used to thread pullbolt to disc.

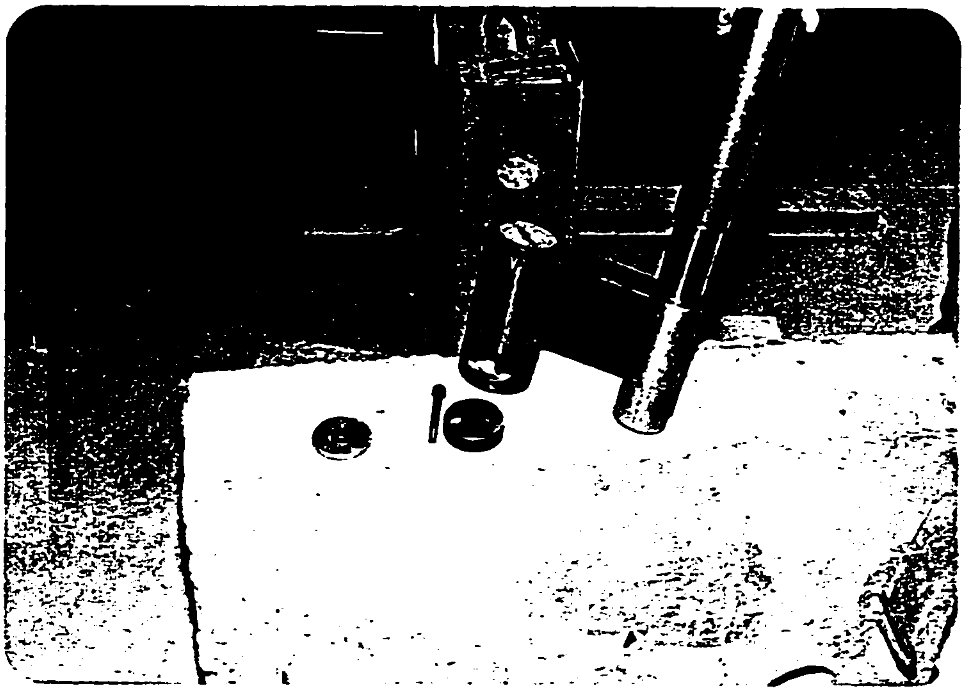


Plate 3.7 Parts of the assembly of Lok test.

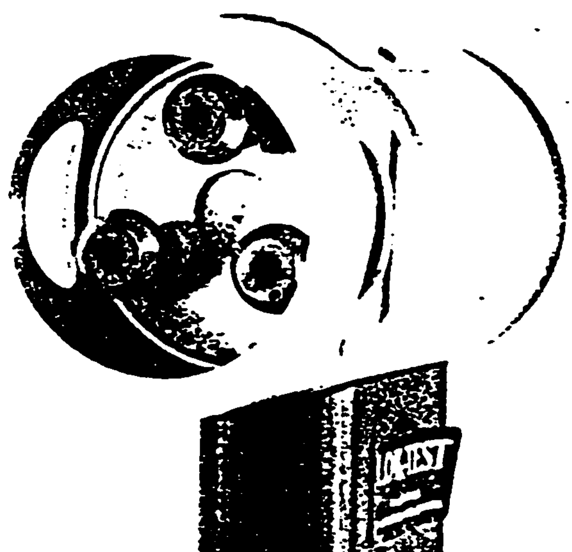


Plate 3.8 The pulling heads of the Lok test instrument.

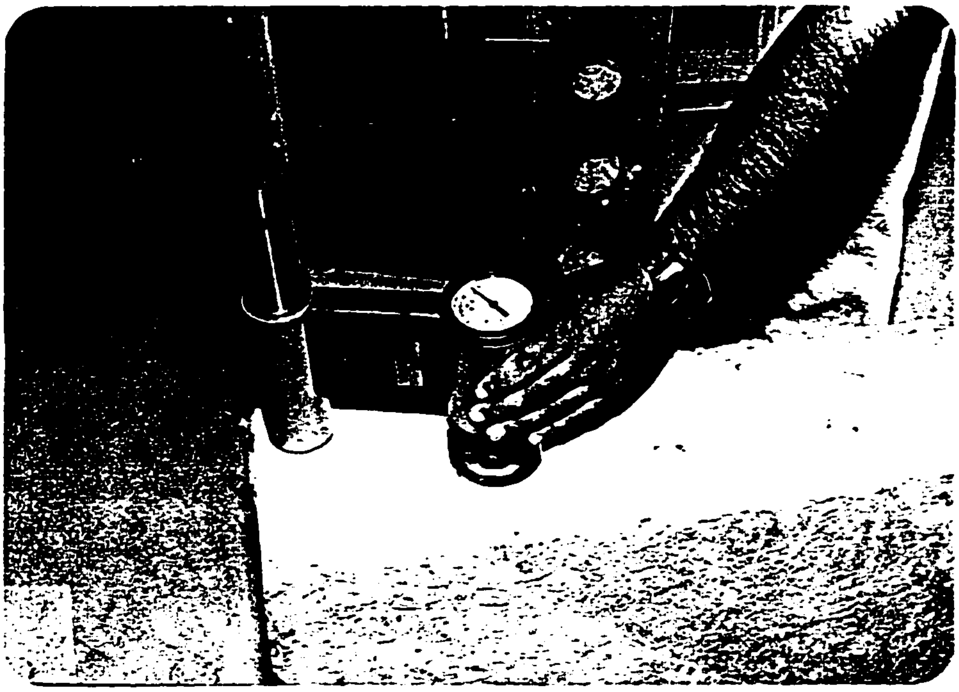


Plate 3.9 Lok test instrument locking to the coupling.

Plate 3.10 Lok test instrument.

Plate 3.11 Concrete surface after a completed Lok-test.

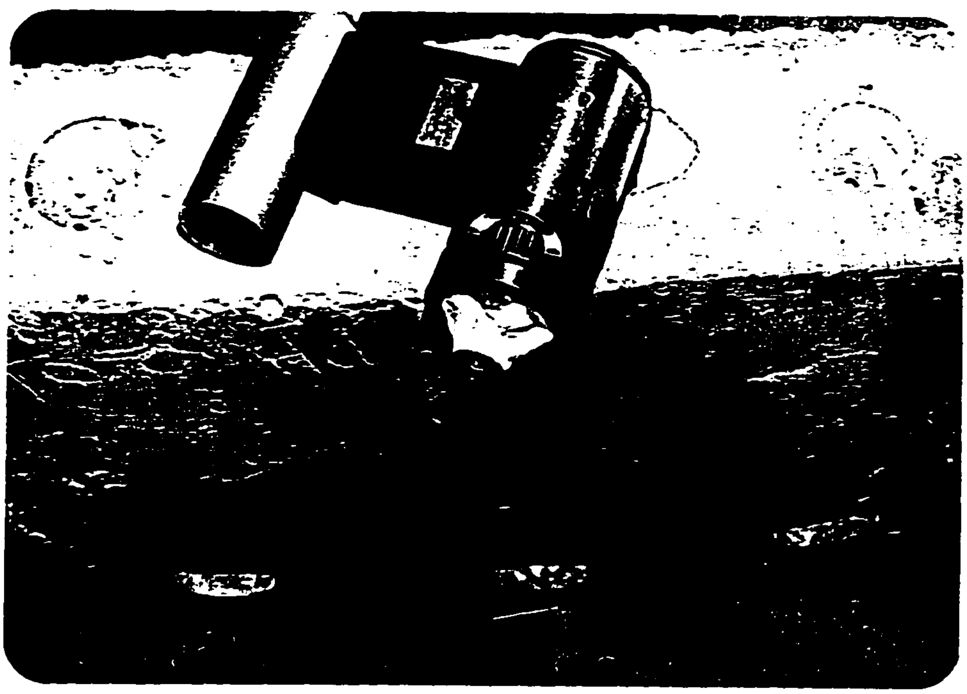


Plate 3.12 The concrete surface after the failure.

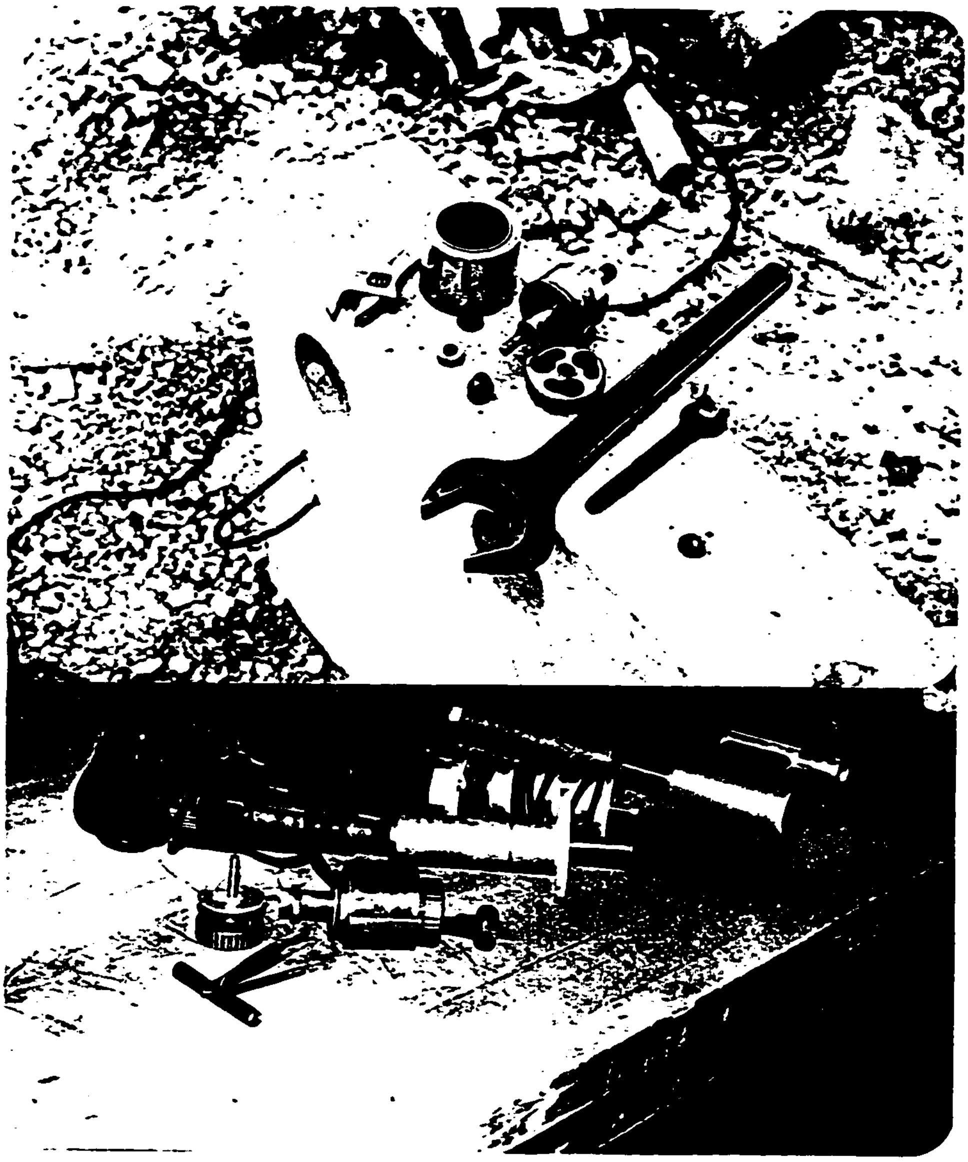


Plate 3.13 Tools used for Capo-test.

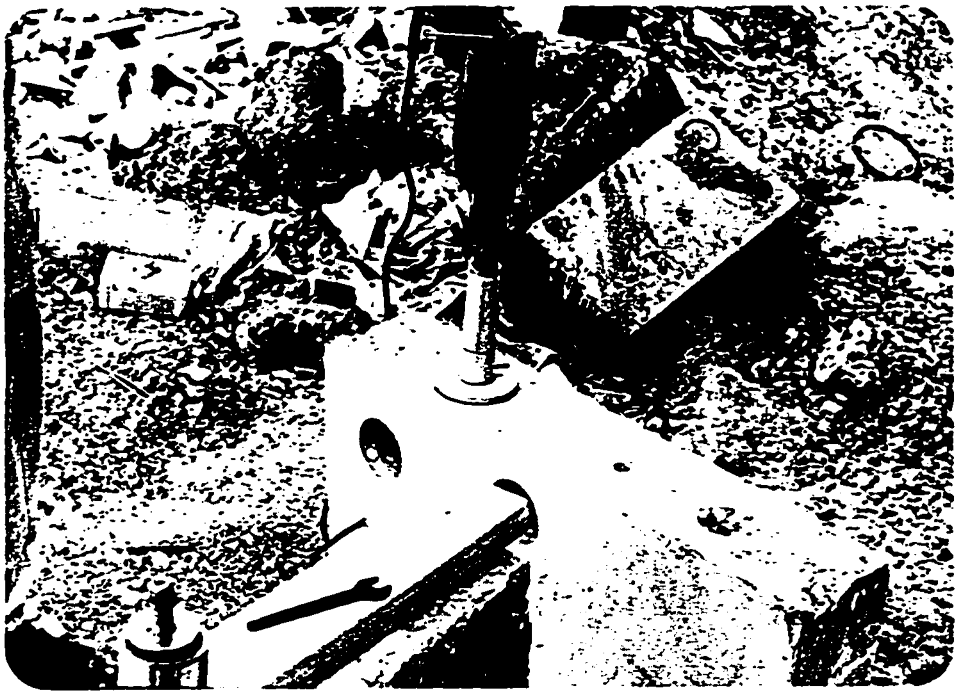


Plate 3.14a Drill-machine during the operation.

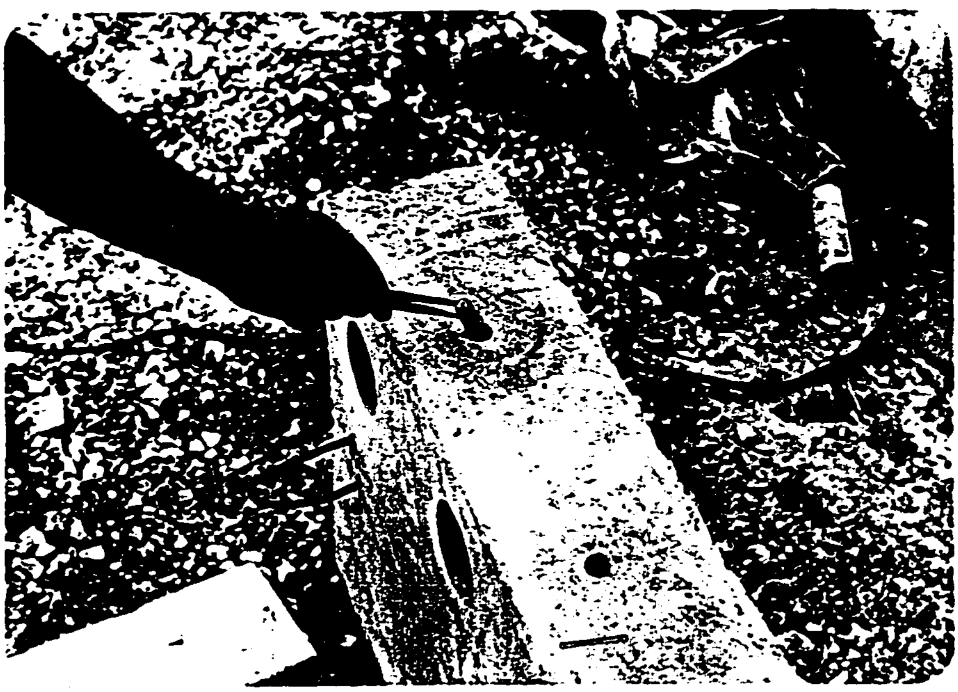


Plate 3.14b Removing the core by using the tweezers.

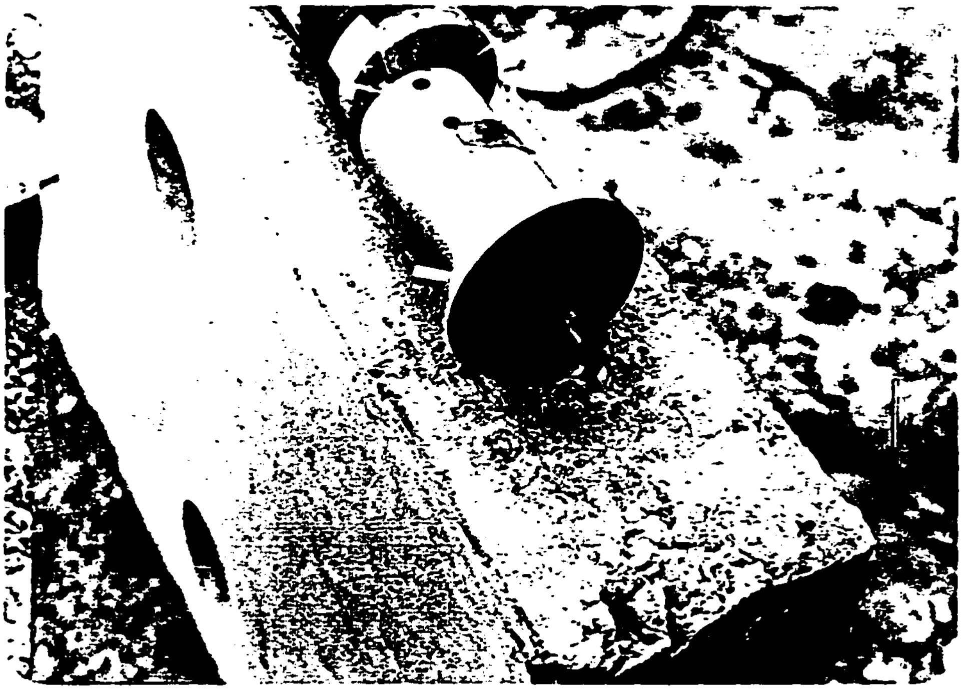


Plate 3.15 The diamond miller.

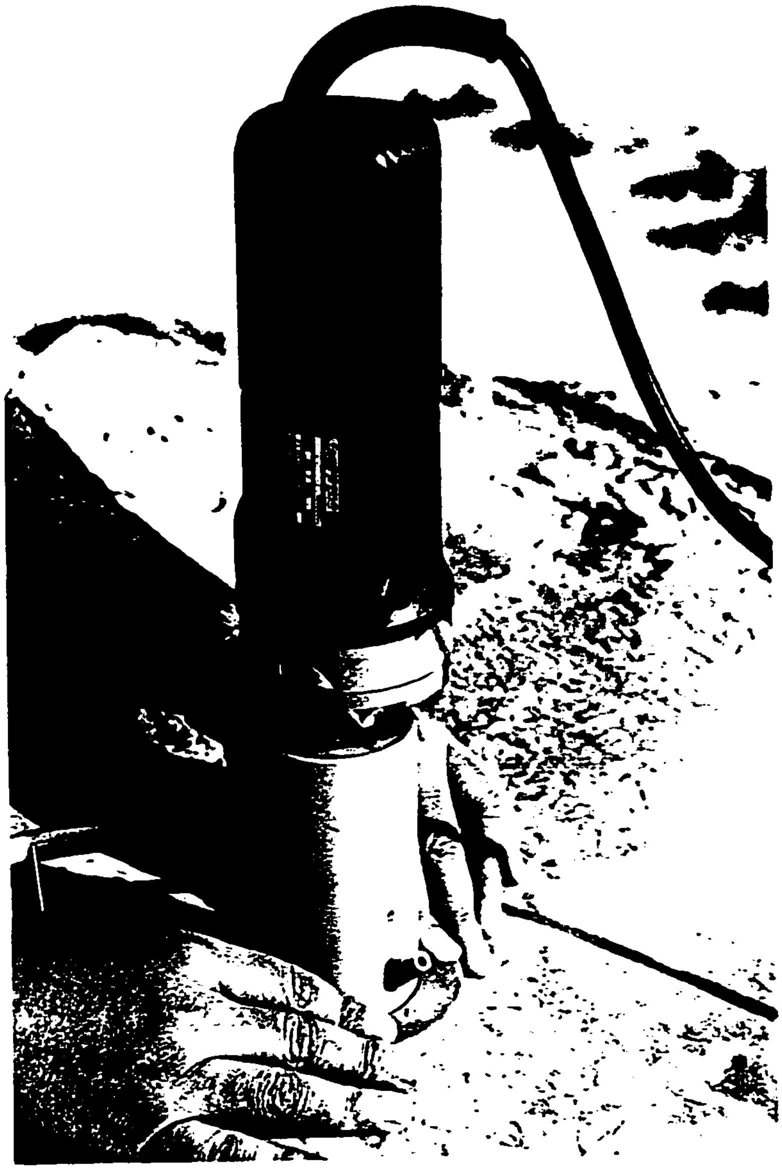


Plate 3.16 Technique used to make a groove in concrete.

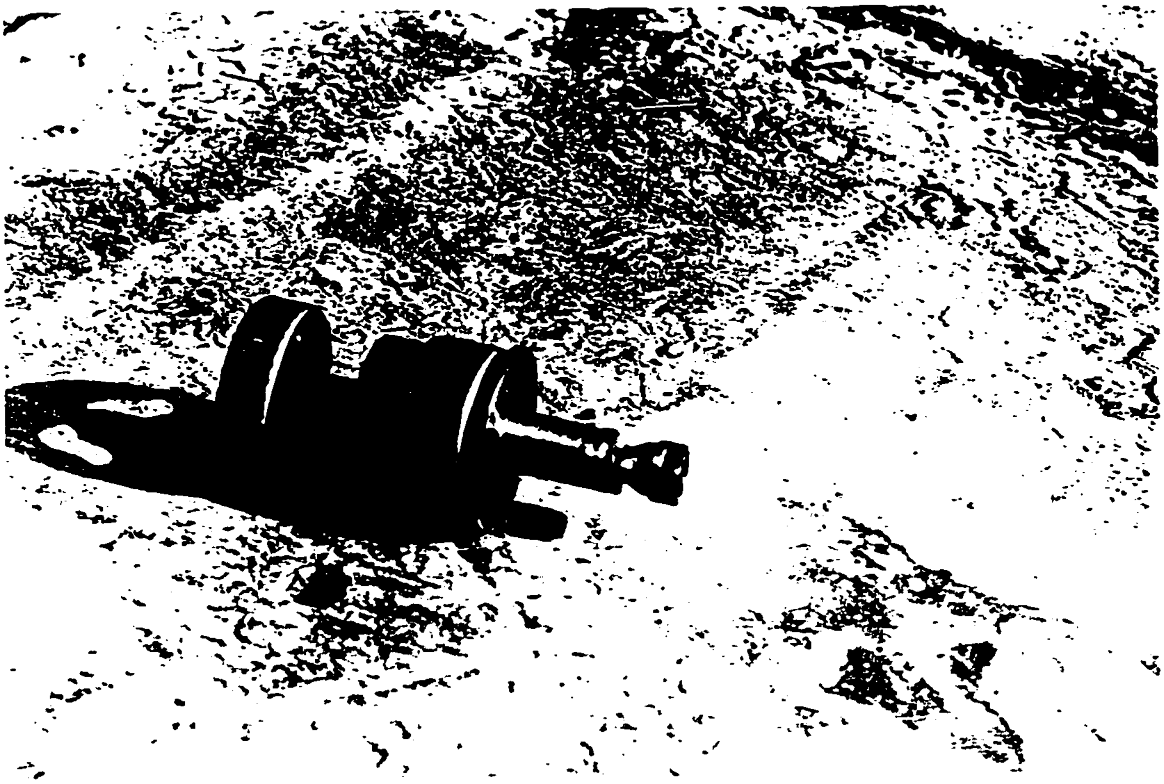


Plate 3.17 The expansion unit assembly.

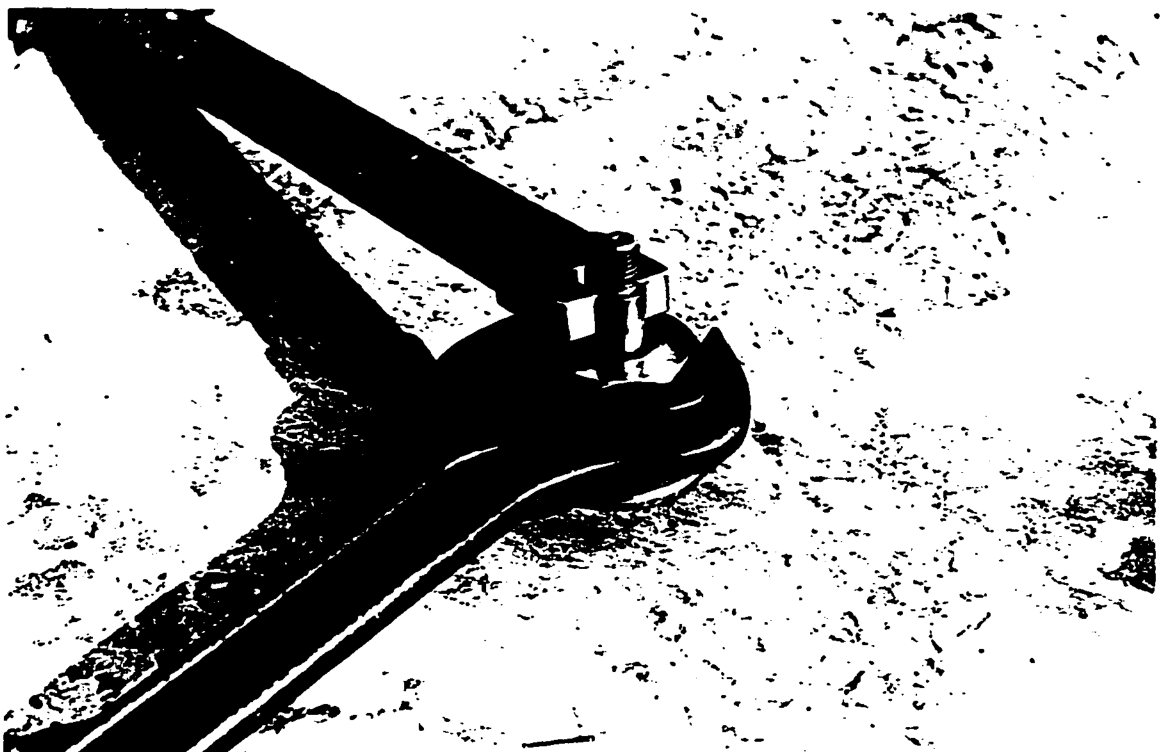


Plate 3.18 Capo insert is expanded to fill the groove.

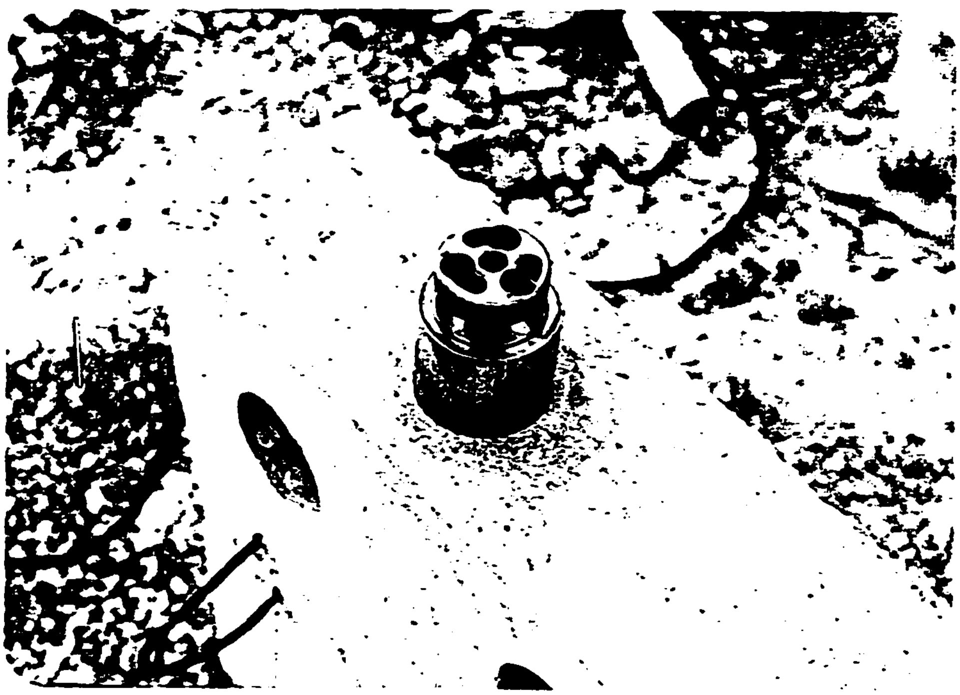


Plate 3.19 The expansion unit before attaching

to the Lok-test instrument.

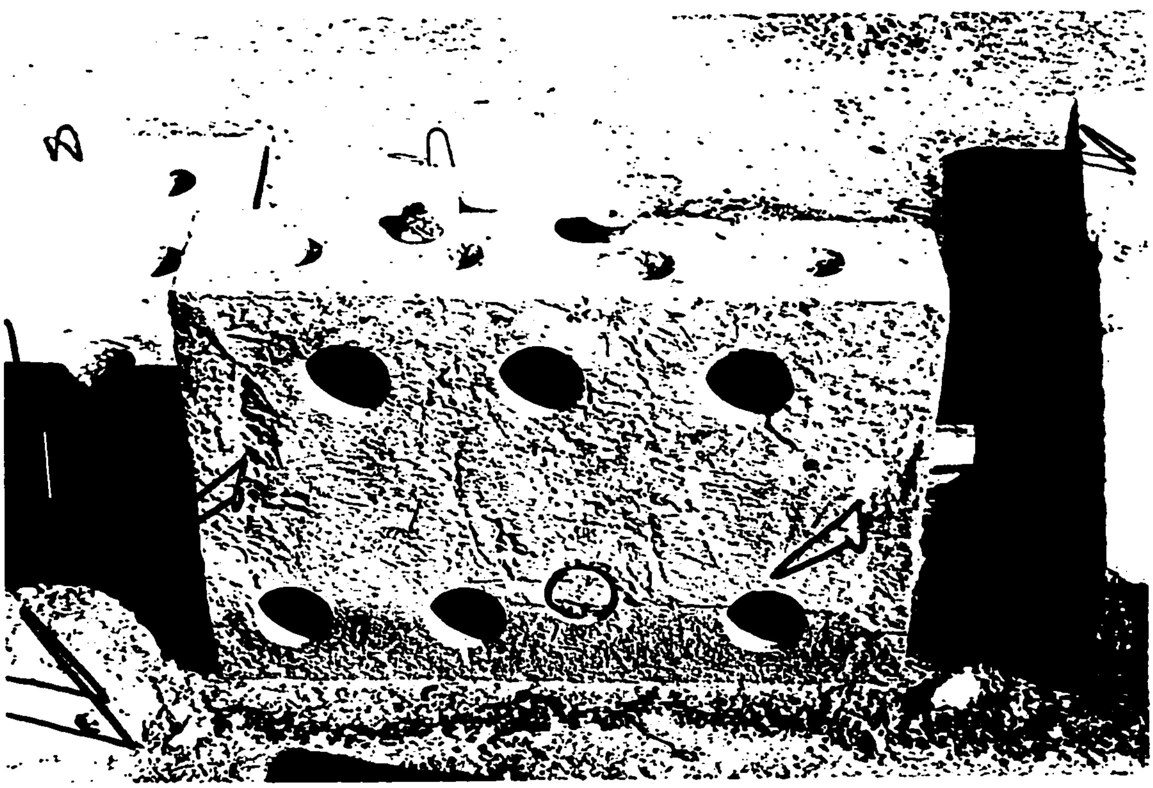


Plate 3.20 The failure cone of Capo-test.

3L

CHAPTER 4
RESULTS AND DISCUSSION

4.1 General:

In this chapter laboratory generated data for Lok-test, Capo-test, cores and compressive strength of cylinders are presented. Based on these data and the parameter of the study, calibration curves for different concrete will be developed using statistical methods.

4.2 Relationship of lok strength and age:

Data for lok strength(L) at different ages generated from the tests on the specimens are shown collectively in Table 4.1a to 4.1h, for Jabel Dhahran' aggregate, and in Table 4.2a to 4.2h, for Abu-Hadriyah aggregate. By using Jabel Dhahran the value of L ranged from about 8.0 kN to 35.0 kN. Also by using Abu-Hadriyah, the value of L ranged from about 14.0 kN to 35.0 kN.

In order to determine the suitable equations, various forms of equations were attempted in regression analysis. The regression analysis was performed using the statistical package SAS . After a number of attempts the following forms of equations were showed better fitting between lok strength and age of concrete in days;

$$L(\text{lok strength}) = a_0 + a_1 D + a_2 D^2 \qquad (4.1a)$$

$$L(\text{lok strength}) = a_0 + a_1 D \qquad (4.1b)$$

The two equations tested, the polynomial type gave relatively better fit with the data for both types of aggregates, and is an acceptable equation for prediction of strength within the range of compressive strength considered in this study since it has better statistical parameters than the linear as shown in Tables 4.3 and 4.4. Using SAS program the values of a0, a1, a2, coefficient of multiple determination R^2 , root of mean square error $\sqrt{MSE}$ and coefficient of variation (C.V) were determined for each type. From Table 4.3, the coefficient of variation for polynomial type ranged from 7.77% to 12.08% and the coefficient of multiple determination ranged from 0.68 to 0.87, whereas the coefficient of variation for linear type ranged from 9.18% to 15.02% and the coefficient of multiple determination ranged from 0.56 to 0.77. In Table 4.4, the coefficient of variation for polynomial type ranged from 4.62% to 9.39% and the coefficient of multiple determination ranged from 0.77 to 0.95, whereas the coefficient of variation for linear type ranged from 6.12% to 10.91% and the coefficient of multiple determination ranged from 0.68 to 0.89.

Table 4.3 shows the values of regression coefficients a0,a1 and a2 within the equations, R^2 , (C.V) and $\sqrt{\overline{MSE}}$ for Eqn.(4.1) and the equations by using Jabel Dhahran aggregate and Table 4.4 shows the same statistical parameters for Abu-Hadriyah. Figs. 4.1a, 4.1b and 4.2a, 4.2b show the graphical representations of the equations, it is clear that lok strength is increasing with increasing age.

4.3 Relationship of lok strength and water-cement ratio:

Laboratory generated data are shown in Table 4.5 for Jabel Dhahran , and Table 4.6 for Abu-Hadriyah. From regression analysis of possible equations which describe the relationship between Lok-strength and W/C ratios, two equations were finally selected. The trial equations were of the following forms:

$$L = b_0+b_1WC+b_2WC^2 \qquad (4.2a)$$

$$L = b_0+b_1WC \qquad (4.2b)$$

The regression coefficients b0 , b1 ,b2 ,coefficient of multiple determination , root of mean square error and coefficient of variation were determined for each equation. The results are shown in Table 4.7 and Table 4.8 .

Between the two equations tested the polynomial type gave relatively better fit with the data for both aggregates, and has better statistical parameters than the linear form. Where in Table 4.7, the coefficient of variation for polynomial type was from 6.40% to 16.0% and the coefficient of multiple determination ranged from 0.61 to 0.94, whereas the coefficient of variation for linear type ranged from 8.54% to 19.50% and the coefficient of multiple determination was from 0.36 to 0.91. From Table 4.8, the coefficient of variation for polynomial type ranged from 4.78% to 19.36% and the coefficient of multiple determination ranged from 0.40 to 0.90, whereas the coefficient of variation for linear type ranged from 4.92% to 18.49% and the coefficient of multiple determination ranged from 0.366 to 0.84. Fig. 4.3a, 4.3b and Fig. 4.4a, 4.4b show the graphical representation of these equations. It is clear that an inverse relationship exists between lok strength and W/C ratio.

4.4 Relationship of lok strength and cement content:

Many forms of equations were attempted in regression analysis. The linear form gave relatively better fit with the data collected for Jabel Dhahran aggregate in Table 4.9. This relationship is shown in Fig. 4.5 for different ages. The models and statistical parameters are shown in Table 4.10 .

4.5 Relationship of capo strength and age:

Data for Capo strength(C) at different ages generated from the tests on the specimens are shown collectively in Table 4.11a to 4.11f, for Jabel Dhahran aggregate, and in Table 4.12a to 4.12f, for Abu-Hadriyah aggregate. By using Jabel Dhahran' the value of C ranged from about 13.0 kN to 34.0 kN. Also by using Abu-Hadriyah, the value of C ranged from about 17.0 kN to 36.0 kN.

Different forms of equations were attempted also in regression analysis for Capo-Tests. From trail runs the following forms of equations showed better fitting between capo strength and days;

$$C(\text{capo strength}) = a_0 + a_1 D + a_2 D^2 \qquad (4.3a)$$

$$C(\text{capo strength}) = a_0 + a_1 D \tag{4.3b}$$

Between the two equations tested, the polynomial type gave relatively better fit with the data for both types of aggregates. Using SAS program the values of a0, a1, a2, coefficient of multiple determination R^2 , root of mean square error $\sqrt{MSE}$ and coefficient of variation (C.V) were determined for each type.

Table 4.13 shows the values of regression coefficients a0,a1 and a2 within the equation, R^2 , (C.V) and $\sqrt{MSE}$ for Eqn.(4.3a) and the equations by using Jabel Dhahran' aggregate and Table 4.14 shows the same statistical parameters for Abu-Hadriyah. Where in Table 4.13, the coefficient of variation for polynomial type was from 6.98% to 13.28% and the coefficient of multiple determination ranged from 0.18 to 0.71, whereas the coefficient of variation for linear type ranged from 6.46% to 12.39% and the coefficient of multiple determination was from 0.16 to 0.69. From Table 4.14, the coefficient of variation for polynomial type ranged from 4.99% to 11.34% and the coefficient of multiple determination ranged from 0.03 to 0.86, whereas the coefficient of variation for linear type ranged from 6.53% to 11.22% and the coefficient of multiple determination ranged from 0.01 to 0.68. Figs. 4.6a, 4.6b and 4.7a, 4.7b show the graphical representations of the previous equations.

4.6 Relationship of capo strength and water-cement ratio:

Laboratory generated data are shown in Table 4.15 for Jabel Dhahran , and Table 4.16 for Abu-Hadriyah. The trial equations which describe the relationship between Capo-strength and W/C ratios, were of the following forms:

$$C = b_0+b_1W_C+b_2W_C^2 \qquad (4.4a)$$

$$C = b_0+b_1W_C \qquad (4.4b)$$

The regression coefficients b0 , b1 ,b2 ,coefficient of multiple determination , root of mean square error and coefficient of variation were determined for each equation. The results are shown in Table 4.17 and Table 4.18.

Between the two equations tested the polynomial type gave relatively better fit with the data for both aggregates, and has better statistical parameters than the linear form.

Where in Table 4.17, the coefficient of variation for polynomial type was from 8.84% to 11.98% and the coefficient of multiple determination ranged from 0.644 to 0.89, whereas the coefficient of variation for linear type ranged from 8.24% to 11.83% and the coefficient of multiple determination was from 0.64 to 0.86. From Table 4.18, the coefficient of variation for polynomial type ranged from 6.51% to 11.78% and the coefficient of multiple determination ranged from 0.34 to 0.91, whereas the coefficient of variation for linear type ranged from 6.23% to 10.91% and the coefficient of multiple determination ranged from 0.33 to 0.90. Fig. 4.8a, 4.8b and Fig. 4.9a, 4.9b show the graphical representation of the previous equations.

4.7 Relationship of compressive strength and age:

Data for compressive strength(Fc) at different ages generated from the test on the specimens are shown collectively in Table 4.1a to 4.1h, for Jabel Dhahran aggregate, and in Table 4.2a to 4.2h, for Abu-Hadriyah aggregate. By using Jabel Dhahran the value of FC ranged from about 8.29 MPa to 36.08 MPa. Also by using Abu-Hadriyah, the value of FC ranged from about 13.85 MPa to

37.94 MPa.

From trail runs the following forms of equations which showed better fitting between compressive strength and days;

$$F_c = a_0 + a_1 D + a_2 D^2 \qquad (4.5a)$$

$$F_c = a_0 + a_1 D \qquad (4.5b)$$

Between the two equations tested, the polynomial type gave relatively better fit with the data for both types of aggregates. Using SAS program the values of a0, a1, a2, coefficient of multiple determination, root of mean square error and coefficient of variation were determined for each type.

Table 4.19 shows the values of regression coefficients a0,a1 and a2 within the equation and the statistical parameters for Eqn.(4.5) and the equations by using Jabel Dhahran aggregate and Table 4.20 shows the same statistical parameters for Abu-Hadriyah. Where in Table 4.19, the coefficient of variation for polynomial type was from 3.60% to 9.39% and the coefficient of multiple determination ranged from 0.89 to 0.98, whereas the coefficient of variation for linear type ranged from 3.72% to 19.15% and the coefficient of multiple determination was from 0.57 to 0.91. From Table 4.20, the coefficient of variation for polynomial type ranged from 4.92% to 9.12% and the coefficient of multiple determination ranged from 0.74 to 0.98, whereas the coefficient of variation for linear type ranged from 6.01% to 13.41% and the coefficient of multiple determination ranged from 0.62 to 0.91. Figs. 4.10a, 4.10b and 4.11a, 4.11b show the graphical representations of these equations which indicate that the compressive strength is increasing with age increasing.

4.8 Relationship of compressive strength and water-cement Ratio:

Laboratory generated data are shown in Table 4.21 for Jabel Dhahran , and Table 4.22 for Abu-Hadriyah. From regression analysis of possible equations which describe the relationship between compressive strength and W/C ratios, two equations were finally selected. The trial equations were of the following forms:

$$F_c = b_o + b_1 WC + b_2 WC^2 \qquad (4.6a)$$

$$F_c = b_o + b_1 WC \qquad (4.6b)$$

The regression coefficient s b0 , b1 ,b2 ,coefficient of multiple determination , root of mean square error (MSE) and coefficient of variation (C.V) and other statistical parameters were determined for each equation. The results are shown in Table 4.23 and Table 4.24.

The polynomial type of equations gave relatively better fit with the data for both aggregates, and has better statistical parameters than the linear form. Where in Table 4.23, the coefficient of variation for polynomial type was from 3.38% to 14.79% and the coefficient of multiple determination ranged from 0.73 to 0.98, whereas the coefficient of variation for linear type ranged from 4.15% to 19.80% and the coefficient of multiple determination was from 0.47 to 0.95. From Table 4.24, the coefficient of variation for polynomial type ranged from 4.63% to 11.40% and the coefficient of multiple determination ranged from 0.60 to 0.96, whereas the coefficient of variation for linear type ranged from 4.83% to 14.72% and the coefficient of multiple determination ranged from 0.36 to 0.93. Figs. 4.12 and 4.13 show the graphical presentation of these equations for Jabel Dhahran and Abu-Hadriyah.

4.9 Relationship of compressive strength and cement content:

Between the two equations tested to correlate compressive strength and cement content, The linear form gave relatively better fit with the data collected in Table 4.25a for Jabel Dhahran aggregate. This relationship is shown in Fig. 4.14 for different ages, and the statistical parameters are shown in Table 4.25b .

4.10 Relationship between lok and compressive strength:

Table 4.26a, 4.26b shows the data for Jabel Dhahran and

Table 4.27a, 4.27b for Abu-Hadriyah. In order to get a prediction model, a calibration equation has been developed using measurements of lok and compressive strength. For this purpose, an analytical predictive equation was developed. It has been shown that the behaviour of the compressive strength is similar to that of lok strength . Thus for a calibration equation the value of FC can be related to L by a linear equation. The calibration equation takes the form :

$$F_C = C_0 + C_1 L \tag{4.7}$$

The calibration equations and statistical parameters are shown in table 4.28 for both types of aggregates. Fig.(4.15a-c) and fig.(4.16a-c) illustrate the representation of calibration equations for both types of aggregate.

4.11 Relationship between capo and compressive strength:

Data for compressive strength and capo strength are shown in Table 4.29a, 4.29b for Jabel Dhahran and Table 4.30a, 4.30b for Abu-Hadriyah. a model has been developed using measurements of Capo and compressive strength. Since the behaviour of the compressive strength is similar to that of capo strength. Thus for a calibration equation the value of FC can be related to C by a linear equation. The calibration equation takes the form :

$$F_C = D_0 + D_1 C \quad (4.8)$$

The calibration equations and statistical parameters are shown in Table 4.31 for both types of aggregates. Fig. 4.17a to 4.17c and Fig. 4.18a to 4.18c illustrate the representation of calibration equations for both types of aggregate.

4.12 Combined Models:

From Table 4.28 which show the relationship between compressive strength of cylinders and lok strength by using different W/C ratios and cement contents, where the calibration equation for Jabel Dhahran is:

$$F_C=-2.60+1.21P_L \qquad (4.9)$$

The coefficient of variation as a function of compressive strength is 10.29 %, the coefficient of correlation is 0.95. For Abu-Hadriyah the equation is:

$$F_C=-2.266+1.23P_L \qquad (4.10)$$

With coefficient of variation equals to 6.98 % and 0.96 as a coefficient of correlation. The combined calibration equation developed by using both types of aggregates is:

$$F_C=-2.95+1.24P_L \qquad (4.11)$$

The coefficient of variation of Eqn. (4.11) is 8.68 %, the coefficient of correlation is 0.96.

In case of Capo-Test, Table 4.31 which show the relationship between compressive strength of cylinders and capo strength by using different W/C ratios and cement contents, where the calibration equation for Jabel Dhahran is:

$$F_C = 1.18 + 1.17P_C \tag{4.12}$$

The coefficient of variation as a function of compressive strength is 8.82 %, the coefficient of correlation is 0.94. For Abu-Hadriyah the equation is:

$$F_C = 2.97 + 1.09P_C \tag{4.13}$$

With coefficient of variation equals to 5.0 % and 0.93 as a coefficient of correlation. The combined calibration equation developed by using both types of aggregates is:

$$F_C = 1.53 + 1.15P_C \tag{4.14}$$

The coefficient of variation of Eqn. (4.14) is 6.82 % and the coefficient of correlation is 0.95. Fig. 4.19a and 4.19b show the combined models for Lok and Capo, where P measured in kN and Fc in MPa.

Table 4.1a: Experimental data for Jabel Dhahran aggregate concrete at 3 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	11.90	10
.70	9.76	9
.70	9.22	8
.65	9.07	13
.65	8.69	12
.65	8.29	12
.55	12.19	16
.55	11.71	15
.55	11.24	14
.45	15.93	16
.45	13.59	13
.45	12.84	12

Table 4.1b: Experimental data for Jabel Dhahran aggregate concrete at 7 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	12.89	13
.70	12.04	11
.70	12.04	10
.65	12.77	17
.65	12.68	16
.65	12.19	13
.55	22.43	20
.55	21.94	19
.55	21.06	17
.45	19.20	22
.45	17.50	15
.45	15.85	14

Table 4.1c: Experimental data for Jabel Dhahran aggregate concrete at 14 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	16.20	17
.70	15.54	15
.70	15.32	13
.65	16.58	17
.65	15.89	17
.65	15.61	17
.55	25.45	23
.55	25.35	19
.55	24.09	17
.45	25.91	25
.45	23.52	25
.45	22.90	23

Table 4.1d: Experimental data for Jabel Dhahran aggregate concrete at 28 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	19.85	19
.70	18.95	17
.70	17.63	16
.65	20.09	21
.65	19.02	18
.65	18.53	17
.55	26.82	23
.55	25.35	22
.55	24.58	21
.45	29.35	28
.45	28.30	28
.45	27.85	26

Table 4.1e: Experimental data for Jabel Dhahran aggregate concrete at 3 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	10.54	15
.70	8.97	13
.70	8.78	12
.65	15.51	16
.65	15.41	15
.65	14.34	11
.55	20.10	17
.55	19.51	17
.55	17.07	16
.45	26.82	24
.45	26.33	24
.45	25.84	23

Table 4.1f: Experimental data for Jabel Dhahran aggregate concrete at 7 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	15.31	16
.70	13.66	15
.70	13.66	14
.65	20.48	17
.65	18.33	16
.65	17.56	16
.55	20.48	20
.55	20.00	19
.55	19.11	17
.45	29.74	28
.45	27.89	25
.45	27.21	25

Table 4.1g: Experimental data for Jabel Dhahran aggregate concrete at 14 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	18.42	16
.70	16.66	16
.70	14.91	15
.65	20.97	22
.65	20.67	18
.65	19.31	17
.55	29.54	25
.55	29.07	24
.55	25.84	21
.45	32.67	32
.45	30.62	31
.45	30.23	28

Table 4.1h: Experimental data for Jabel Dhahran aggregate concrete at 28 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	20.39	18
.70	19.73	17
.70	19.30	15
.65	25.35	21
.65	24.18	20
.65	22.92	19
.55	30.72	27
.55	30.72	25
.55	29.74	23
.45	36.08	35
.45	35.59	30
.45	33.65	28

Table 4.2a: Experimental data for Abu-Hadriyah aggregate concrete at 3 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	16.29	17
.65	14.53	17
.65	13.85	14
.55	17.75	19
.55	17.26	18
.55	16.09	16
.45	25.35	23
.45	24.48	20
.45	23.40	17

Table 4.2b: Experimental data for Abu-Hadriyah aggregate concrete at 7 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	21.36	19
.65	19.31	17
.65	18.73	16
.55	25.35	19
.55	23.89	19
.55	23.50	18
.45	30.23	28
.45	28.38	26
.45	27.50	26

Table 4.2c: Experimental data for Abu-Hadriyah aggregate concrete at 14 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	25.16	22
.65	24.09	21
.65	22.82	19
.55	29.07	26
.55	28.31	24
.55	28.04	21
.45	36.08	31
.45	33.74	27
.45	25.78	26

Table 4.2d: Experimental data for Abu-Hadriyah aggregate concrete at 28 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	26.53	25
.65	26.33	23
.65	24.96	22
.55	30.72	29
.55	29.25	25
.55	26.53	24
.45	36.28	32
.45	35.40	32
.45	34.62	31

Table 4.2e: Experimental data for Abu-Hadriyah aggregate concrete at 3 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	17.05	16
.65	14.59	15
.65	13.97	14
.55	16.58	18
.55	16.58	17
.55	15.21	15
.45	24.38	22
.45	23.60	21
.45	21.74	21

Table 4.2f: Experimental data for Abu-Hadriyah aggregate concrete at 7 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	23.40	21
.65	22.82	18
.65	21.26	18
.55	23.40	23
.55	21.46	20
.55	20.48	19
.45	29.45	24
.45	28.48	24
.45	27.80	23

Table 4.2g: Experimental data for Abu-Hadriyah aggregate concrete at 14 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	26.33	26
.65	25.65	23
.65	24.87	20
.55	30.95	25
.55	30.23	23
.55	28.24	22
.45	34.70	30
.45	33.58	29
.45	28.87	28

Table 4.2h: Experimental data for Abu-Hadriyah aggregate concrete at 28 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	31.20	26
.65	30.72	26
.65	28.97	25
.55	35.83	29
.55	33.29	28
.55	32.85	27
.45	37.94	35
.45	36.86	32
.45	35.45	31

Table 4.3: Relationships between lok strength and age for Jabel Dhahran aggregate and statistical parameters.

W/C	CC	Model	$\sqrt{MSE}$	C.V	R^2
.45	400	$P = 20.705 + .971D - .0215D^2$	2.17	7.81	0.72
.45	400	$P = 24.063 + 0.2836D$	2.548	9.18	0.574
.55	400	$P = 13.75 + 0.918D - 0.018D^2$	1.625	7.77	0.85
.55	400	$P = 16.62 + .331D$	2.01	9.59	0.75
.65	400	$P = 12.017 + 0.717D - 0.015D^2$	1.85	10.65	0.68
.65	400	$P = 14.424 + .2238D$	2.057	11.86	0.56
.45	300	$P = 9.09 + 1.455D - .0286D^2$	2.487	12.08	0.87
.45	300	$P = 13.56 + .541D$	3.092	15.02	0.77
.55	300	$P = 13.776 + .633D - .012D^2$	1.905	10.11	0.69
.55	300	$P = 15.685 + .242D$	2.0	10.62	0.61
.65	300	$P = 10.82 + .651D - .0133D^2$	1.48	9.355	0.76
.65	300	$P = 12.90 + .226D$	1.685	10.64	0.66

Table 4.4: Relationships between lok strength and age for Abu-Hadriyah aggregate and statistical parameters.

W/C	CC	Model	$\sqrt{MSE}$	C.V	R^2
.45	400	$P = 18.24 + .974D - .0163D^2$	1.233	4.62	0.945
.45	400	$P = 20.79 + 0.452D$	1.63	6.12	0.89
.55	400	$P = 14.75 + 0.817D - 0.0124D^2$	1.60	7.22	0.90
.55	400	$P = 16.68 + .422D$	1.747	7.88	0.86
.65	400	$P = 12.056 + 1.10D - 0.022D^2$	1.736	8.40	0.88
.65	400	$P = 15.50 + .398D$	2.25	10.91	0.77
.45	300	$P = 17.96 + 1.109D - .0223D^2$	2.47	9.31	0.78
.45	300	$P = 21.45 + .395D$	2.82	10.60	0.68
.55	300	$P = 15.783 + .66D - .011D^2$	2.035	9.39	0.77
.55	300	$P = 17.42 + .327D$	2.06	9.53	0.73
.65	300	$P = 14.16 + .57D - .0086D^2$	1.52	7.85	0.83
.65	300	$P = 15.50 + .295D$	1.56	8.07	0.80

Table 4.5: Experimental Lok strength (in kN) at different ages (in days) for Jabel Dhahran aggregate.

W/C	CC	3 days	7 days	14 days	28 days
.70	300	9.00	11.33	15.00	17.33
.65	300	12.33	15.33	17.00	18.67
.55	300	15.00	18.67	19.67	22.00
.45	300	13.67	17.00	24.33	27.33
.70	400	13.33	15.00	15.67	16.67
.65	400	14.00	16.33	19.00	20.00
.55	400	16.67	18.67	23.33	25.00
.45	400	23.67	26.00	30.33	31.00

Table 4.6: Experimental Lok strength (in kN) at different ages (in days) for Abu-Hadriyah aggregate.

W/C	CC	3 days	7 days	14 days	28 days
.65	300	16.00	17.33	20.67	23.33
.55	300	17.67	18.67	23.67	26.00
.45	300	20.00	26.67	28.00	31.67
.65	400	15.00	19.00	23.00	25.67
.55	400	16.67	20.67	23.33	28.00
.45	400	21.33	23.67	29.00	32.67

Table 4.7: Relationships between Lok strength and W/C for Jabel Dhahran aggregate and statistical parameters.

DAY	CC	Model	$\sqrt{MSE}$	C.V	R^2
28	400	$P=57.46-60.7wc+3.85wc^2$	2.144	9.255	0.894
28	400	$P=56.23-56.27wc$	2.034	8.78	0.894
14	400	$P=71.68-114.9wc+50.59wc^2$	1.95	8.836	0.91
14	400	$P=55.47-56.84wc$	1.886	8.54	0.91
7	400	$P=102.6-253.6wc+184.8wc^2$	1.22	6.40	0.94
7	400	$P=43.45-41.47wc$	1.75	9.18	0.86
3	400	$P=98.6-247.56wc+180.1wc^2$	1.507	8.91	0.91
3	400	$P=40.88-40.79wc$	1.92	11.35	0.83
28	300	$p=71.63-136.3wc+84.09wc^2$	1.417	6.644	0.908
28	300	$P=44.70-39.77wc$	1.47	6.90	0.89
14	300	$P=54.94-88.9wc+45.9wc^2$	1.835	9.66	0.83
14	300	$p=40.24-36.16wc$	1.77	9.32	0.822
7	300	$P=57.3+285.4wc-267.5wc^2$	2.497	16.03	0.613
7	300	$P=28.40-21.81wc$	3.04	19.50	0.36
3	300	$P=-47.2+233.7wc-219.1wc^2$	1.222	9.78	0.815
3	300	$P=23.00-17.85wc$	1.94	15.45	0.483

Table 4.8: Relationships between lok strength and W/c for Abu-Hadriyya aggregate and statistical parameters.

DAY	CC	Model	$\sqrt{MSE}$	C.V	R^2
28	400	$p=82.54-163.33wc+116.67wc^2$	1.374	4.776	0.87
28	400	$p=48.03-35.00wc$	1.417	4.92	0.84
14	400	$p=120.50-323.33wc+266.67wc^2$	2.03	8.08	0.734
14	400	$p=41.61-30.00wc$	2.36	9.39	0.58
7	400	$p=53.67-96.67wc+66.67wc^2$	1.60	7.57	0.69
7	400	$p=33.94-23.33wc$	1.52	7.21	0.668
3	400	$p=79.46-196.67wc+150.0wc^2$	1.11	6.26	0.898
3	400	$p=35.08-31.67wc$	1.30	7.36	0.836
28	300	$p=94.29-206.67wc+150.0wc^2$	1.795	6.65	0.849
28	300	$p=49.92-41.67wc$	1.845	6.83	0.814
14	300	$p=64.0-110.0wc+66.67wc^2$	2.285	9.48	0.722
14	300	$p=44.28-36.67wc$	2.146	8.90	0.715
7	300	$p=85.58-213.33wc+166.67wc^2$	3.83	19.36	0.404
7	300	$p=36.28-30.00wc$	3.66	18.49	0.366
3	300	$p=38.75-56.67wc+33.33wc^2$	2.186	12.22	0.458
3	300	$p=28.89-20.00wc$	2.03	11.36	0.45

Table 4.9: Experimental data for Jabel Dhahran aggregate concrete by using different cement contents, W/C=0.55 .

CC	AGE	FC (MPa)	LOK (kN)
300	28	25.58	21.00
300	14	24.96	19.67
300	3	11.71	15.0
350	28	27.79	22.00
350	14	25.16	19.00
350	3	20.79	15.0
400	28	30.40	25.00
400	14	26.33	23.33
400	3	18.90	16.67
450	28	29.90	25.00
450	14	27.00	23.00
450	3	22.91	18.00

Table 4.10:The relationship between Lok strength and cement content for Jabel Dhahran aggregate and statistical parameters

DAY	Model	$\sqrt{MSE}$	C.V	COR
28	$P = 11.84 + 0.031CC$	1.06	4.53	0.92
14	$P = 6.51 + 0.041CC$	1.47	6.74	0.91
3	$P = 16.17 - 0.003CC$	1.34	8.85	0.5

Table 4.11a: Experimental data for Jabel Dhahran aggregate concrete at 14 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.70	16.20	15
.70	15.54	14
.70	15.32	13
.65	16.58	16
.65	15.89	15
.65	15.61	13
.55	25.45	21
.55	25.35	18
.55	24.09	15
.45	25.91	22
.45	23.52	20
.45	22.90	18

Table 4.11b: Experimental data for Jabel Dhahran aggregate concrete at 28 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.70	19.85	18
.70	18.95	16
.70	17.63	14
.65	20.09	17
.65	19.02	15
.65	18.53	14
.55	26.82	21
.55	25.35	19
.55	24.58	17
.45	29.35	25
.45	28.30	23
.45	27.85	19

Table 4.11c: Experimental data for Jabel Dhahran aggregate concrete at 91 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	20.85	19
.65	19.51	18
.65	17.10	16
.55	26.22	23
.55	24.90	20
.55	24.01	18
.45	29.65	26
.45	28.94	24
.45	27.25	21

Table 4.11d: Experimental data for Jabel Dhahran aggregate concrete at 14 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.70	18.42	16
.70	16.66	14
.70	14.91	13
.65	20.97	19
.65	20.67	18
.65	19.31	16
.55	29.54	22
.55	29.07	19
.55	25.84	18
.45	32.67	30
.45	30.62	28
.45	30.23	26

Table 4.11e: Experimental data for Jabel Dhahran aggregate concrete at 28 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.70	20.39	18
.70	19.73	15
.70	19.30	13
.65	25.35	21
.65	24.18	17
.65	22.92	16
.55	30.72	24
.55	30.72	21
.55	29.74	20
.45	36.08	30
.45	35.59	29
.45	33.65	27

Table 4.11f: Experimental data for Jabel Dhahran aggregate concrete at 91 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	25.84	24
.65	23.89	22
.65	23.40	20
.55	33.64	29
.55	33.15	26
.55	32.67	24
.45	37.54	34
.45	36.57	32
.45	33.15	29

Table 4.12a: Experimental data for Abu-Hadriyah aggregate concrete at 14 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	25.16	19
.65	24.09	18
.65	22.82	17
.55	29.07	24
.55	28.31	24
.55	28.04	22
.45	36.08	29
.45	33.74	28
.45	25.78	25

Table 4.12b: Experimental data for Abu-Hadriyah aggregate concrete at 28 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	26.53	24
.65	26.33	20
.65	24.96	18
.55	30.72	27
.55	29.25	26
.55	26.53	23
.45	36.28	30
.45	35.40	28
.45	34.62	26

Table 4.12c: Experimental data for Abu-Hadriyah aggregate concrete at 91 days, cement content=300 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	27.40	26
.65	26.72	24
.65	25.10	21
.55	31.20	29
.55	29.57	26
.55	27.23	22
.45	36.51	31
.45	35.28	28
.45	34.70	25

Table 4.12d: Experimental data for Abu-Hadriyah aggregate concrete at 14 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	26.33	24
.65	25.65	22
.65	24.87	20
.55	30.95	25
.55	30.23	22
.55	28.24	22
.45	34.70	30
.45	33.58	27
.45	28.87	24

Table 4.12e: Experimental data for Abu-Hadriyah aggregate concrete at 28 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	31.20	26
.65	30.72	25
.65	28.97	23
.55	35.83	29
.55	33.29	27
.55	32.85	26
.45	37.94	32
.45	36.86	30
.45	35.45	26

Table 4.12f: Experimental data for Abu-Hadriyah aggregate concrete at 91 days, cement content=400 kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	32.55	28
.65	30.79	28
.65	29.64	27
.55	37.88	31
.55	36.25	30
.55	34.14	29
.45	38.39	36
.45	37.22	31
.45	35.53	28

Table 4.13: Relationships between capo strength and age for Jabel Dhahran aggregate and statistical parameters.

W/C	CC	Model	$\sqrt{MSE}$	C.V	R^2
.45	400	$P=27.33+.048D-.000D^2$	2.055	6.98	0.475
.45	400	$P=27.33+0.0476D$	1.90	6.46	0.475
.55	400	$P=17.32+0.18D-0.0009D^2$	2.23	9.91	0.71
.55	400	$P=18.89+.0828D$	2.11	9.344	0.69
.65	400	$P=17.54+0.002D-.0005D^2$	2.11	10.97	0.567
.65	400	$P=16.629+.0585D$	1.965	10.22	0.56
.45	300	$P=16.93+0.246D-.0019D^2$	2.56	11.64	0.34
.45	300	$P=20.25+.04D$	2.51	11.43	0.26
.55	300	$P=16.74+.099D-.0007D^2$	2.54	13.28	0.18
.55	300	$P=17.89+.028D$	2.37	12.39	0.16
.65	300	$P=13.95+.053D-.00014D^2$	1.53	9.61	0.52
.65	300	$P=14.19+.038D$	1.42	8.91	0.51

Table 4.14: Relationships between capo strength and age for Abu-Hadriyah aggregate and statistical parameters.

W/C	CC	Model	$\sqrt{MSE}$	C.V	R^2
.45	400	$P = 24.01 + .237D - .0017D^2$	3.40	11.59	0.32
.45	400	$P = 26.97 + 0.053D$	3.23	11.03	0.28
.55	400	$P = 17.31 + 0.455D - 0.0035D^2$	1.45	5.43	0.86
.55	400	$P = 23.41 + .076D$	2.04	7.62	0.67
.65	400	$P = 17.64 + 0.348D - 0.003D^2$	1.247	4.99	0.84
.65	400	$P = 22.23 + .062D$	1.63	6.53	0.68
.45	300	$P = 26.42 + 0.074D - .00062D^2$	2.40	8.65	0.025
.45	300	$P = 27.51 + .006D$	2.24	8.07	0.01
.55	300	$P = 20.63 + .22D - .0018D^2$	2.45	9.89	0.21
.55	300	$P = 23.77 + .023D$	2.40	9.70	0.11
.65	300	$P = 14.61 + .27D - .0019D^2$	2.36	11.34	0.59
.65	300	$P = 17.87 + .066D$	2.33	11.22	0.53

Table 4.15: Experimental Capo strength (in kN) at different ages (in days) for Jabel Dhahran aggregate.

W/C	CC	14 days	28 days	91 days
.70	300	14.00	16.00	...
.65	300	14.67	15.33	17.67
.55	300	18.00	19.00	20.33
.45	300	20.00	22.33	23.67
.70	400	14.33	15.33	...
.65	400	17.67	18.00	22.00
.55	400	19.67	21.67	26.33
.45	400	28.00	28.67	31.67

Table 4.16: Experimental Capo strength (in kN) at different ages (in days) for Abu-Hadriyah aggregate.

W/C	CC	14 days	28 days	91 days
.65	300	18.00	20.67	23.67
.55	300	23.33	25.33	25.67
.45	300	27.33	28.00	28.00
.65	400	22.00	25.33	27.67
.55	400	23.00	27.33	30.00
.45	400	27.00	29.33	31.67

Table 4.17: Relationships between capo strength and W/C for Jabel Dhahran aggregate and statistical parameters.

DAY	CC	Model	$\sqrt{MSE}$	C.V	R^2
91	400	$p=68.04-103.33wc+0.50wc^2$	2.36	8.84	0.81
91	400	$P=53.25-48.33wc$	2.20	8.24	0.80
28	400	$P=79.15-151.66wc+87.10wc^2$	2.16	10.34	0.88
28	400	$p=51.25-51.64wc$	2.14	10.25	0.865
14	400	$P=93.55-207.88wc+136.85wc^2$	2.02	10.14	0.89
14	400	$P=49.72-50.73wc$	2.15	10.79	0.86
91	300	$p=46.92-66.67wc+33.33wc^2$	2.23	10.88	0.644
91	300	$P=37.06-30.00wc$	2.08	10.11	0.64
28	300	$P=61.27-123.78wc+83.59wc^2$	2.177	11.98	0.68
28	300	$p=34.50-27.80wc$	2.15	11.83	0.65
14	300	$P=28.53-14.54wc-9.38wc^2$	1.94	11.62	0.68
14	300	$P=31.54-25.31wc$	1.84	11.03	0.677

Table 4.18: Relationships between capo strength and W/c for Abu-Hadriyya aggregate and statistical parameters.

DAY	CC	Model	$\sqrt{MSE}$	C.V	R^2
91	400	$p=30.92+16.67wc-33.33wc^2$	2.43	8.15	0.41
91	400	$p=40.78-20.00wc$	2.25	7.57	0.40
28	400	$p=38.33-20.00wc+3.11wc^2$	2.00	7.32	0.50
28	400	$p=38.33-20.00wc$	1.852	6.77	0.50
14	400	$p=82.13-190.0wc+150.0wc^2$	2.31	9.62	0.57
14	400	$p=37.75-25.00wc$	2.28	9.52	0.51
91	300	$p=42.63-40.00wc+16.67wc^2$	3.04	11.78	0.34
91	300	$p=37.69-21.67wc$	2.81	10.91	0.337
28	300	$p=15.25+73.33wc-100.00wc^2$	2.43	9.838	0.70
28	300	$p=44.83-36.67wc$	2.31	9.36	0.68
14	300	$p=28.83+26.67wc-66.67wc^2$	1.49	6.51	0.91
14	300	$p=48.56-46.67wc$	1.43	6.23	0.90

Table 4.19: Relationships between compressive strength and age for Jabel Dhahran aggregate and statistical parameters.

W/C	CC	Model	$\sqrt{MSE}$	C.V	R^2
.45	400	$F_c = 24.74 + .55D - .0064D^2$	1.09	3.60	0.93
.45	400	$F_c = 25.74 + 0.345D$	1.12	3.72	0.91
.55	400	$F_c = 14.32 + 1.24D - 0.024D^2$	1.94	7.96	0.89
.55	400	$F_c = 18.00 + .49D$	2.47	10.15	0.81
.65	400	$F_c = 13.77 + 0.644D - 0.01D^2$	1.28	6.51	0.89
.65	400	$F_c = 15.31 + .33D$	1.39	7.11	0.86
.45	300	$F_c = 10.14 + 1.29D - .0227D^2$	1.44	6.82	0.95
.45	300	$F_c = 13.69 + .57D$	2.09	9.94	0.89
.55	300	$F_c = 7.29 + 2.07D - .051D^2$	1.97	9.39	0.91
.55	300	$F_c = 15.25 + .44D$	4.02	19.15	0.57
.65	300	$F_c = 6.14 + .981D - .0184D^2$	0.60	4.22	0.98
.65	300	$F_c = 9.01 + .393D$	1.41	9.95	0.90

Table 4.20: Relationships between compressive strength and age for Abu-Hadriyah aggregate and statistical parameters.

W/C	CC	Model	$\sqrt{MSE}$	C.V	R^2
.45	400	$F_c = 20.16 + 1.25D - .025D^2$	2.16	7.20	0.86
.45	400	$F_c = 24.03 + 0.46D$	2.68	8.94	0.76
.55	400	$F_c = 10.41 + 1.94D - 0.037D^2$	1.29	4.98	0.98
.55	400	$F_c = 16.26 + .74D$	2.89	11.14	0.88
.65	400	$F_c = 16.50 + 0.86D - 0.013D^2$	1.19	4.92	0.94
.65	400	$F_c = 18.55 + .44D$	1.46	6.01	0.91
.45	300	$F_c = 21.98 + 0.99D - .0182D^2$	2.75	9.12	0.74
.45	300	$F_c = 24.82 + .41D$	2.99	9.63	0.68
.55	300	$F_c = 12.76 + 1.77D - .043D^2$	1.49	6.04	0.93
.55	300	$F_c = 19.43 + .40D$	3.30	13.41	0.62
.65	300	$F_c = 11.47 + 1.32D - .029D^2$	1.18	5.56	0.95
.65	300	$F_c = 15.94 + 0.402D$	2.29	10.83	0.77

Table 4.21: Experimental Compressive strength (in MPa) at different ages (in days) for Jabel Dahran aggregate.

W/C	CC	3 days	7 days	14 days	28 days	91days
.70	300	10.29	12.32	15.69	18.81	...
.65	300	8.68	12.55	16.03	19.21	19.15
.55	300	11.71	21.81	24.96	25.58	25.04
.45	300	14.21	17.52	24.11	28.50	28.61
.70	400	9.43	14.21	16.66	19.80	...
.65	400	15.09	18.79	20.32	24.15	24.38
.55	400	18.90	19.86	28.15	30.40	33.15
.45	400	26.33	28.28	31.17	35.11	35.75

Table 4.22: Experimental Compressive strength (in MPa) at different ages (in days) for Abu-Hadriyah aggregate.

W/C	CC	3 days	7 days	14 days	28 days	91days
.65	300	14.89	19.80	24.02	25.94	26.40
.55	300	17.03	24.25	28.47	28.83	29.33
.45	300	24.41	28.70	31.87	35.43	35.50
.65	400	15.20	22.49	25.62	30.30	30.99
.55	400	16.09	21.78	29.64	34.00	36.09
.45	400	23.24	28.58	32.38	36.75	37.05

Table 4.23a: Relationships between compressive strength and W/C for Jabel Dhahran aggregate and statistical parameters.

DAY	Model	$\sqrt{MSE}$	C.V	R^2
91	$F_c = -28.98 + 282.83wc - 308.83wc^2$	1.55	5.00	0.94
91	$F_c = 62.38 - 56.88wc$	2.19	7.04	0.85
28	$F_c = 30.46 + 55.80wc - 101.24wc^2$	0.93	3.38	0.98
28	$F_c = 62.88 - 60.46wc$	1.14	4.15	0.97
14	$F_c = 7.35 + 125.92wc - 161.56wc^2$	1.54	6.40	0.95
14	$F_c = 59.09 - 59.59wc$	1.86	7.72	0.92
7	$F_c = 84.38 - 174.0wc + 107.58wc^2$	1.92	9.45	0.90
7	$F_c = 49.93 - 50.45wc$	1.97	9.73	0.88
3	$F_c = 50.05 - 47.17wc - 13.83wc^2$	1.53	8.75	0.95
3	$F_c = 54.48 - 63.05wc$	1.45	8.32	0.95

CC= 400 Kg/ m^3

Table 4.23b: Relationships between compressive strength and W/C for Jabel Dhahran aggregate and statistical parameters.

DAY	Model	$\sqrt{MSE}$	C.V	R^2
91	$F_c = 15.97 + 80.30wc - 116.00wc^2$	1.46	6.00	0.91
91	$F_c = 50.29 - 47.30wc$	1.49	6.12	0.90
28	$F_c = 42.46 - 22.84wc - 16.98wc^2$	1.32	5.71	0.93
28	$F_c = 47.90 - 42.34wc$	1.25	5.44	0.93
14	$F_c = -17.52 + 179.78wc - 191.63wc^2$	2.01	9.97	0.84
14	$F_c = 43.85 - 40.27wc$	2.35	11.62	0.77
7	$F_c = -68.11 + 333.45wc - 315.32wc^2$	2.37	14.79	0.74
7	$F_c = 32.87 - 28.63wc$	3.18	19.80	0.47
3	$F_c = 53.14 - 129.95wc + 97.11wc^2$	1.31	11.68	0.73
3	$F_c = 22.04 - 18.44wc$	1.42	12.68	0.65

CC = 300 Kg/ m^3

Table 4.24a: Relationships between compressive strength and W/C for Abu-Hadriyah aggregate and statistical parameters.

DAY	Model	$\sqrt{MSE}$	C.V	R^2
91	$F_c = -9.88 + 197.43wc - 207.00wc^2$	1.61	4.63	0.80
91	$F_c = 51.36 - 30.27wc$	1.85	5.34	0.70
28	$F_c = 22.19 + 70.87wc - 89.83wc^2$	1.93	5.77	0.69
28	$F_c = 48.76 - 27.95wc$	1.85	5.53	0.66
14	$F_c = -27.67 + 235.70wc - 236.50wc^2$	1.51	5.22	0.78
14	$F_c = 42.30 - 24.45wc$	1.88	6.53	0.59
7	$F_c = 152.10 - 443.47wc + 375.50wc^2$	1.17	4.83	0.91
7	$F_c = 41.01 - 30.42wc$	2.28	9.40	0.60
3	$F_c = 175.19 - 555.47wc + 484.00wc^2$	1.28	6.61	0.89
3	$F_c = 32.00 - 23.07wc$	2.84	14.72	0.36

CC= 400 Kg/ m^3

Table 4.24b: Relationships between compressive strength and W/C for Abu-Hadriyah aggregate and statistical parameters.

DAY	Model	$\sqrt{MSE}$	C.V	R^2
91	$F_C = 103.29-223.47wc + 161.83wc^2$	1.44	4.74	0.91
91	FsubC = 55.41-45.45wc	1.59	5.23	0.88
28	$F_c = 111.00-251.33wc-185.33wc^2$	1.41	4.68	0.92
28	$F_C = 56.18-47.47wc$	1.64	5.44	0.88
14	$F_C = 34.06 + 18.90wc-52.83wc^2$	3.21	11.40	0.60
14	$F_C = 49.69-39.22wc$	2.98	10.60	0.60
7	$F_C = 48.88-45.07wc + 0.50wc^2$	1.27	5 22	0.93
7	$F_C = 48.73-44.52wc$	1.17	4.83	0.93
3	$F_C = 122.37-335.43wc + 261.67wc^2$	1.04	5.56	0.96
3	$F_C = 44.96-47.60wc$	1.70	9.05	0.87

CC= 300 Kg/ m^3

Table 4.25a: Experimental data for Jabel Dhahran aggregate concrete by using different cement contents, W/C=0.55 .

CC	AGE	FC (MPa)	LOK (kN)
300	28	25.58	21.00
300	14	24.96	19.67
300	3	11.71	15.0
350	28	27.79	22.00
350	14	25.16	19.00
350	3	20.79	15.0
400	28	30.40	25.00
400	14	26.33	23.33
400	3	18.90	16.67
450	28	29.90	25.00
450	14	27.00	23.00
450	3	22.91	18.00

Table 4.25b:the relationship between compressive strength and CC for Jabel Dhahran aggregate and statistical parameters.

DAY	Model	$\sqrt{MSE}$	C.V	COR
28	$F_c = 17.24 + 0.029CC$	0.61	2.17	0.97
14	$F_c = 20.40 + 0.015CC$	0.29	1.10	0.97
3	$F_c = -5.21 + 0.063CC$	3.21	17.30	0.84

Table 4.26a: Experimental data for Jabel Dhahran aggregate concrete for different W/C ratios, cement content=300kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	10.29	9.00
.70	12.32	11.33
.70	15.69	15.00
.70	18.81	17.33
.65	8.68	12.33
.65	12.55	15.33
.65	16.03	17.00
.65	19.21	18.67
.55	11.71	15.00
.55	21.81	18.67
.55	24.96	19.67
.55	25.58	22.00
.45	14.12	13.67
.45	17.52	17.00
.45	24.11	24.33
.45	28.50	27.33

Table 4.26b: Experimental data for Jabel Dhahran aggregate concrete for different W/C ratios, cement content=400kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.70	9.43	13.33
.70	14.21	15.00
.70	16.66	15.67
.70	19.80	16.67
.65	15.09	14.00
.65	18.79	16.33
.65	20.32	19.00
.65	24.15	20.00
.55	18.90	16.67
.55	19.86	18.67
.55	28.15	23.33
.55	30.40	25.00
.45	26.33	23.67
.45	28.28	26.00
.45	31.17	30.33
.45	35.11	31.00

Table 4.27a: Experimental data for Abu-Hadriyah aggregate concrete for different W/C ratios, cement content=300kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	14.89	16.00
.65	19.80	17.33
.65	24.02	20.67
.65	25.94	23.33
.55	17.03	17.67
.55	24.25	18.67
.55	28.47	23.67
.55	28.83	26.00
.45	24.41	20.00
.45	28.70	26.67
.45	31.87	28.00
.45	35.43	31.67

Table 4.27b: Experimental data for Abu-Hadriyah aggregate concrete for different W/C ratios, cement content=400kg/ m^3.

W/C	FC (MPa)	LOK (kN)
.65	15.20	15.00
.65	22.49	19.00
.65	25.62	23.00
.65	30.30	25.67
.55	16.09	16.67
.55	21.78	20.67
.55	29.64	23.33
.55	34.00	28.00
.45	23.24	21.33
.45	28.58	23.67
.45	32.38	29.00
.45	36.75	32.67

Table 4.28: Relationships between compressive and lok strength for both types of aggregate and statistical parameters.

Aggr.	CC	Model	$\sqrt{MSE}$	C.V	COR
J-DH.	300	$F_c = -2.42 + 1.17P_L$	2.34	13.27	0.93
J-DH.	400	$F_c = -2.31 + 1.21P_L$	2.00	8.97	0.96
J-DH.	300&400	$F_c = -2.60 + 1.21P_L$	2.06	10.29	0.95
AB-H.	300	$F_c = -0.854 + 1.162P_L$	2.00	7.91	0.95
AB-H.	400	$F_c = -3.81 + 1.299P_L$	1.725	6.55	0.97
AB-H.	300&400	$F_c = -2.266 + 1.23P_L$	1.8	6.98	0.96
J.+AB.	300&400	$F_c = -2.95 + 1.24P_L$	1.95	8.68	0.96

F_c in MPa

P_L in kN

Table 4.29a: Experimental data for Jabel Dhahran aggregate concrete for different W/C ratios, cement content=300kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.70	15.69	14.00
.70	18.81	16.00
.65	16.03	14.67
.65	19.21	15.33
.65	19.15	17.67
.55	24.96	18.00
.55	25.58	19.00
.55	25.04	20.33
.45	24.11	20.00
.45	28.50	22.33
.45	28.61	23.67

Table 4.29b: Experimental data for Jabel Dhahran aggregate concrete for different W/C ratios, cement content=400kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.70	16.66	14.33
.70	19.80	15.33
.65	20.32	17.66
.65	24.15	18.00
.65	24.38	22.00
.55	28.15	19.67
.55	30.40	21.67
.55	33.15	26.33
.45	31.17	28.00
.45	35.11	28.67
.45	35.75	31.67

Table 4.30a: Experimental data for Abu-Hadriyah aggregate concrete for different W/C ratios, cement content=300kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	24.02	18.00
.65	25.94	20.67
.65	26.40	23.67
.55	28.47	23.33
.55	28.83	25.33
.55	29.33	25.67
.45	31.87	27.33
.45	35.43	28.00
.45	35.50	28.00

Table 4.30b: Experimental data for Abu-Hadriyah aggregate concrete for different W/C ratios, cement content=400kg/ m^3.

W/C	FC (MPa)	CAP (kN)
.65	25.62	22.00
.65	30.30	23.67
.65	30.99	27.67
.55	29.64	23.00
.55	34.00	27.33
.55	36.09	30.00
.45	32.38	27.00
.45	36.75	29.33
.45	37.05	31.67

Table 4.31: Relationships between compressive and capo strengt for both types of aggregate and statistical parameters.

Aggr.	CC	Model	$\sqrt{MSE}$	C.V	COR
J-DH.	300	$F_c = -3.44 + 1.41P_c$	1.665	7.45	0.94
J-DH.	400	$F_c = 3.90 + 1.05P_c$	2.49	9.15	0.87
J-DH.	300&400	$F_c = 1.18 + 1.17P_c$	2.18	8.82	0.94
AB-H.	300	$F_c = 3.19 + 1.08P_c$	1.78	6.01	0.91
AB-H.	400	$F_c = 3.89 + 1.07P_c$	1.49	4.59	0.93
AB-H.	300&400	$F_c = 2.97 + 1.09P_c$	1.55	4.99	0.93
J. + AB.	300&400	$F_c = 1.53 + 1.15P_c$	1.88	6.82	0.95

F_c in MPa

P_c in kN

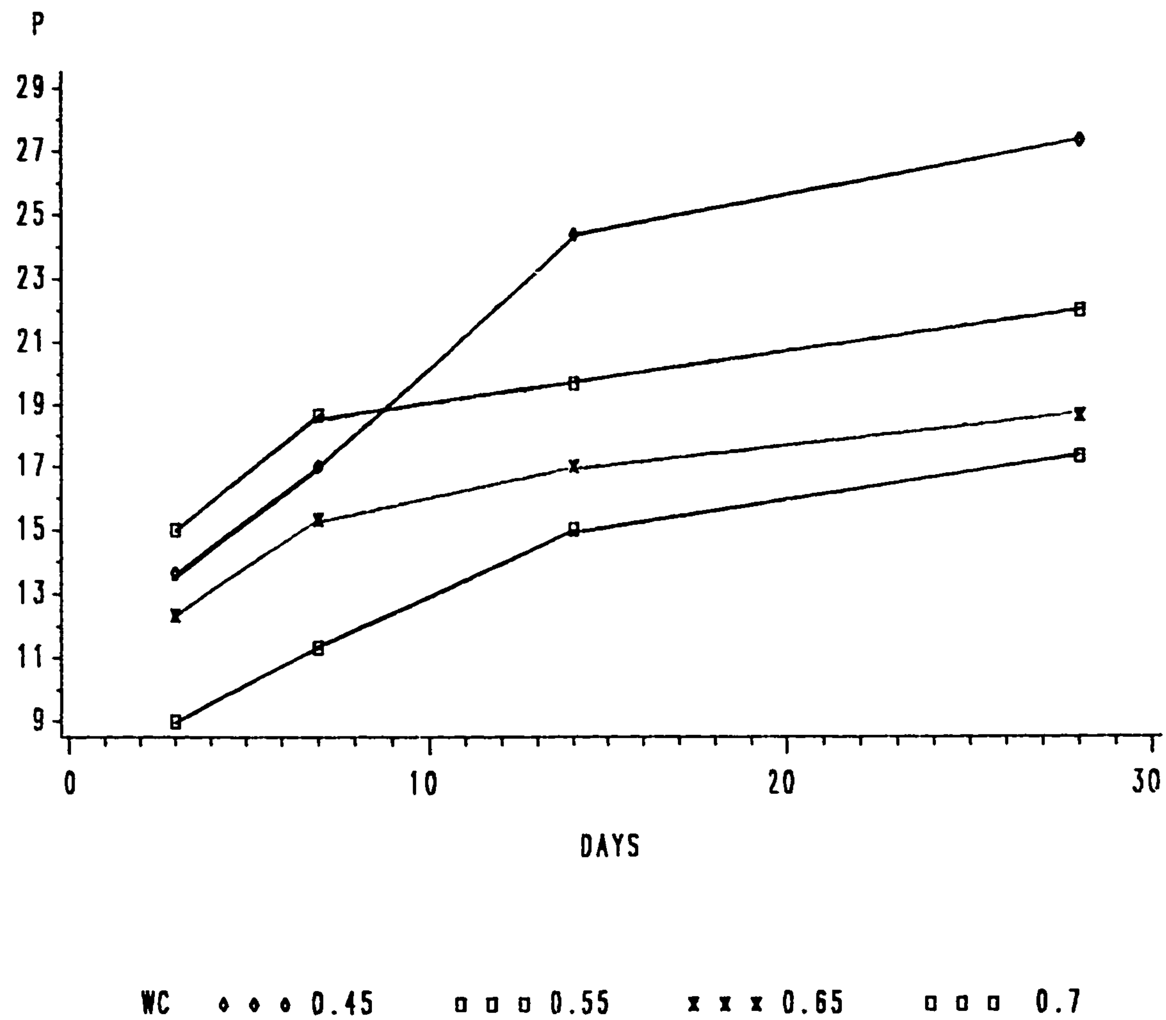
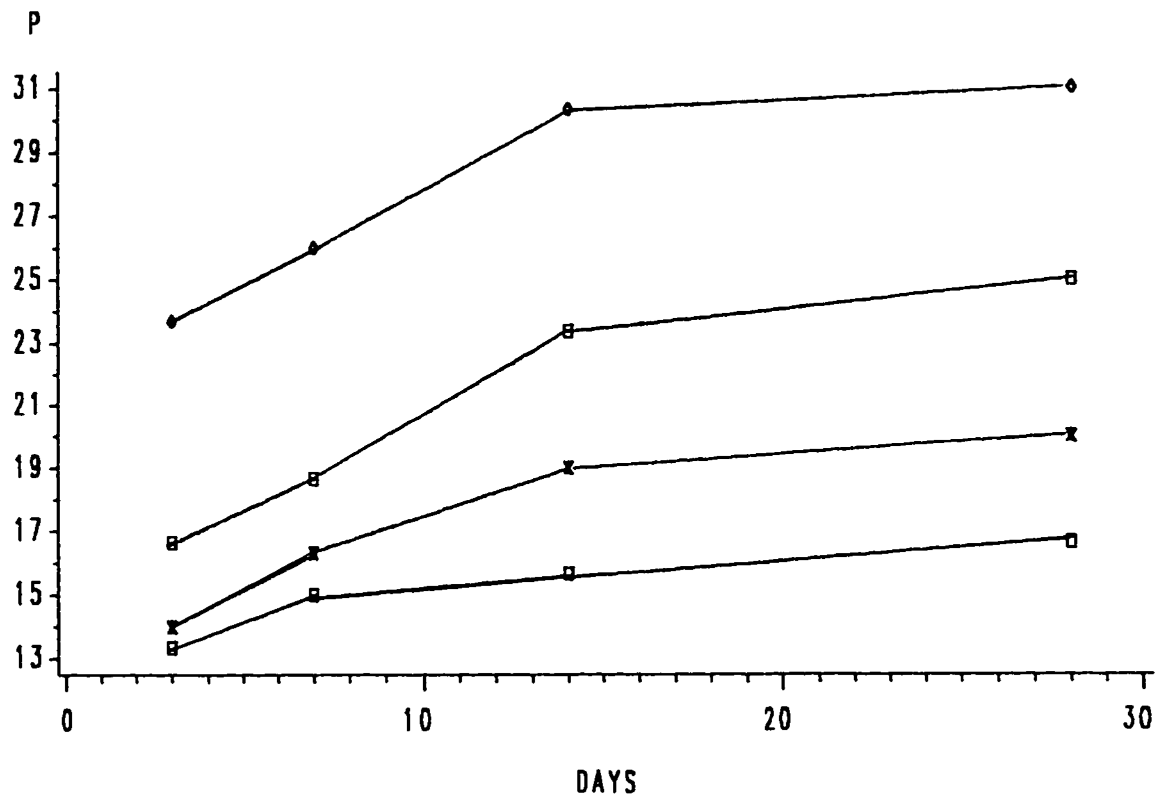


FIG. 4.1A RELATIONSH;P OF LOK-STRENGTH AND AGE FOR J. DH., CC=300



WC ◇ ◇ ◇ 0.45 □ □ □ 0.55 ⵝ ⵝ ⵝ 0.65 □ □ □ 0.7

FIG. 4.1B RELATIONSHIP OF LOK-STRENGTH AND AGE FOR J. DH., CC=400

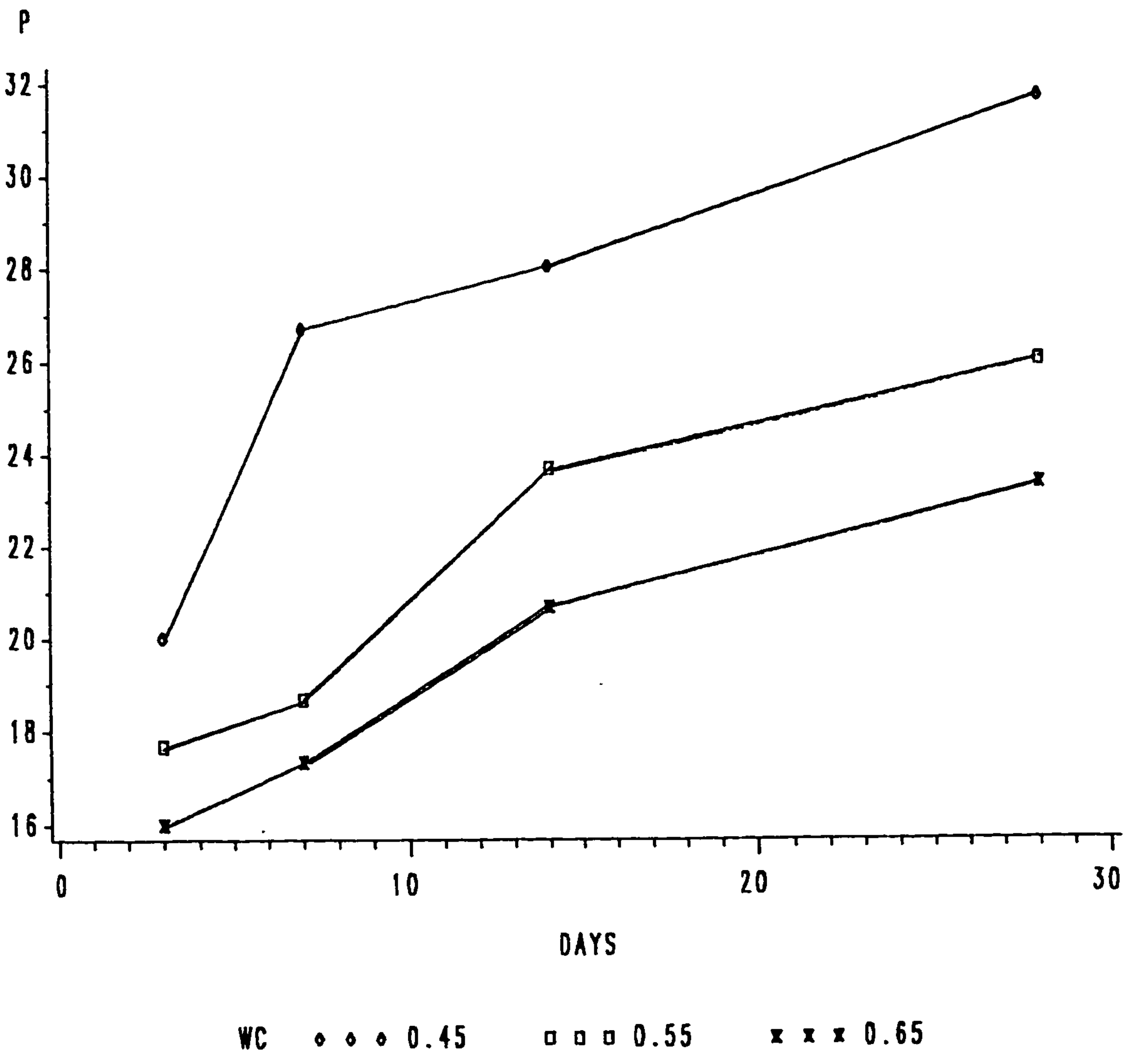


FIG. 4.2A: RELATIONSHIP OF LOK AND AGE FOR ABU-HAD. , CC= 300

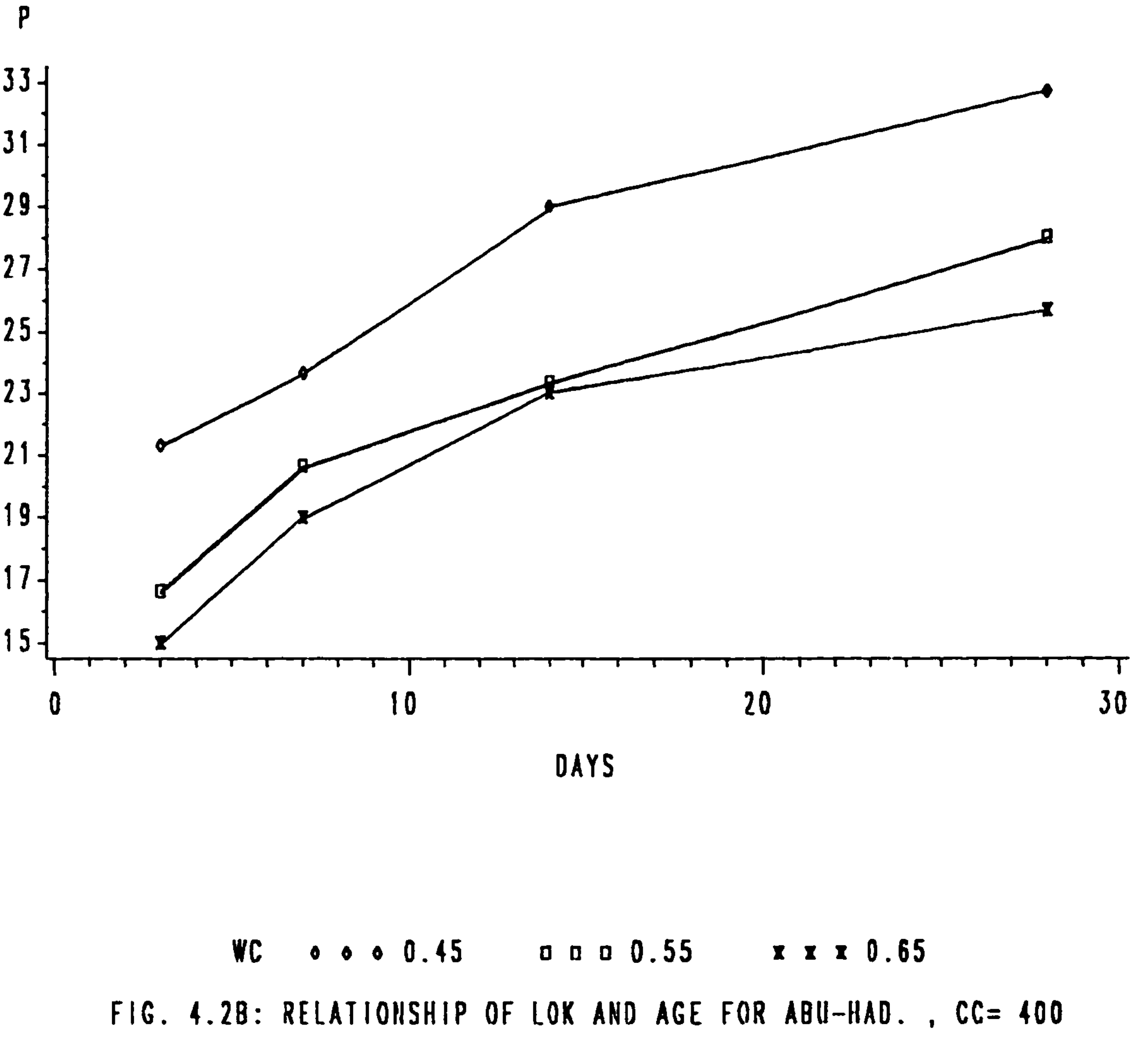
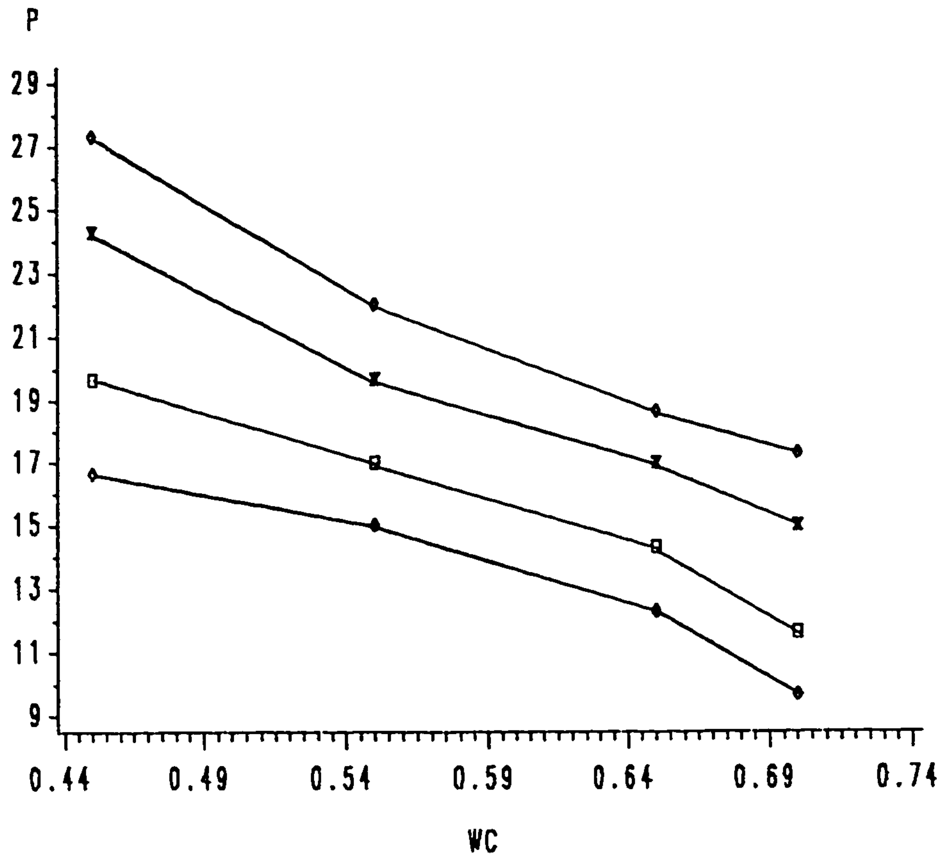


FIG. 4.28: RELATIONSHIP OF LOK AND AGE FOR ABU-HAD. , CC= 400



DAYS ◇ ◇ ◇ 3 □ □ □ 7 x x x 14 ◇ ◇ ◇ 28

FIG. 4.3A: RELATIONSHIP OF LOK STRENGTH AND W/C FOR J. DH., CC=300

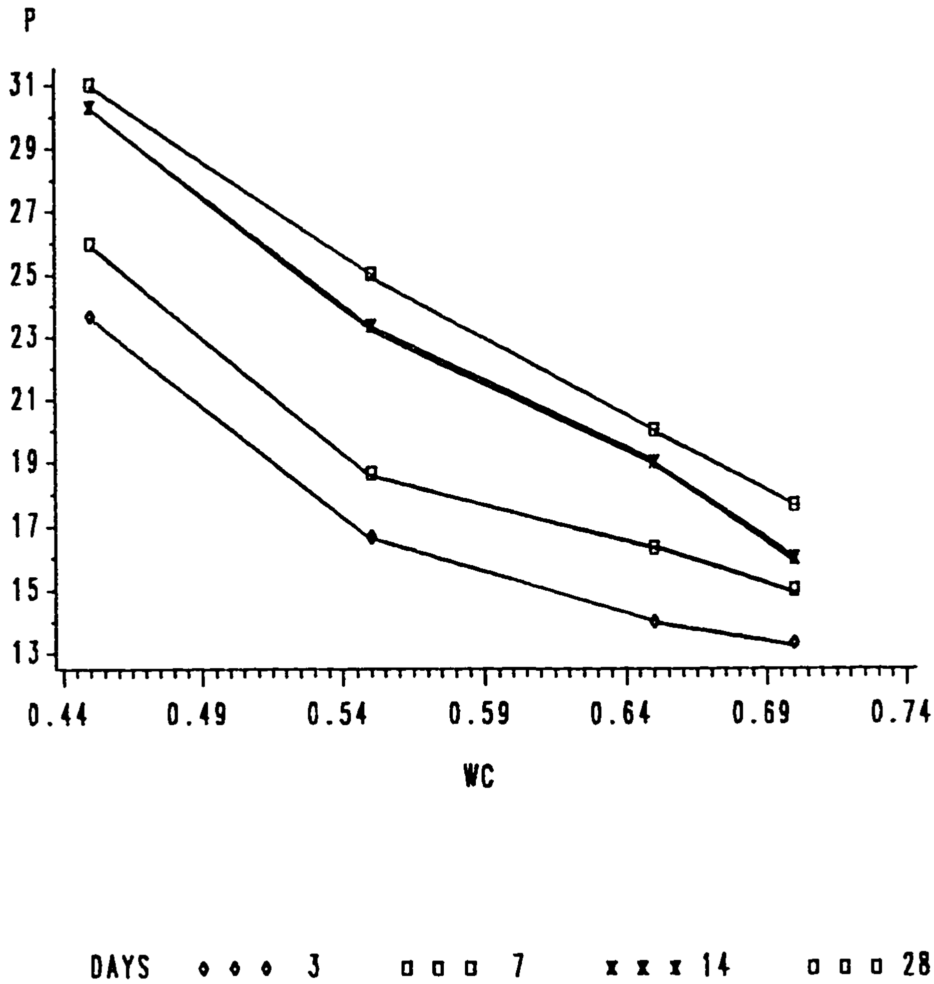


FIG. 4.3B:RELATIONSHIP OF LOK STRENGTH AND W/C FOR J. OH.,CC=400

:3L

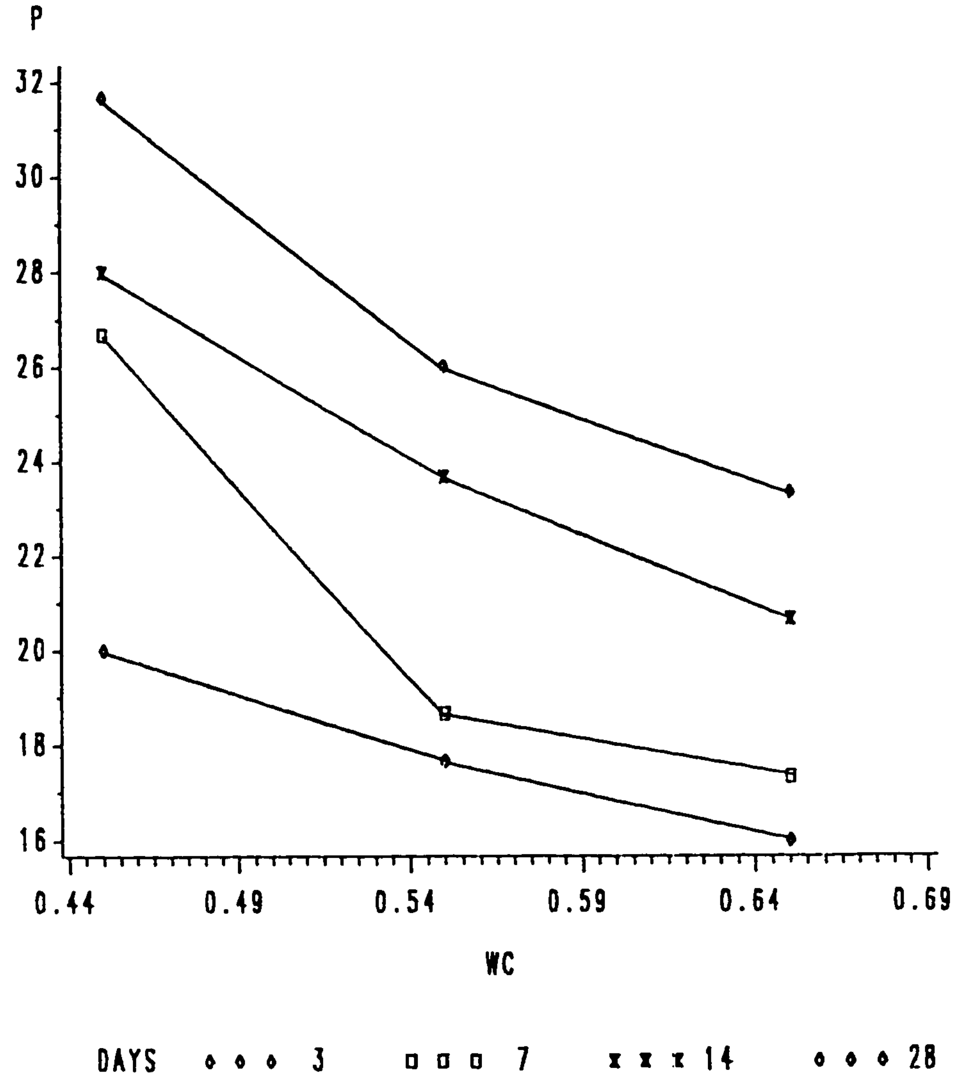
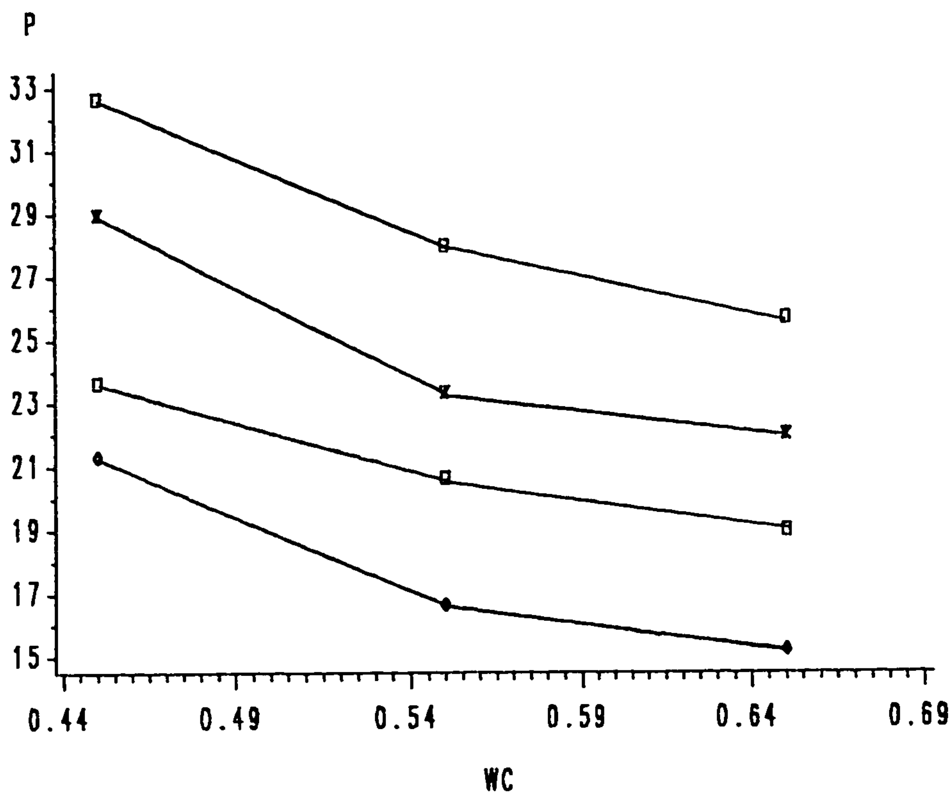


FIG. 4.4A: RELATIONSHIP OF LOK STRENGTH AND W/C FOR ABU.HAD, CC=300



DAYS ◇◇◇ 3 □□□ 7 ⧗⧗⧗ 14 □□□ 28

FIG. 4.4B: RELATIONSHIP OF LOK STRENGTH AND W/C FOR ABU-HAD.,CC=400

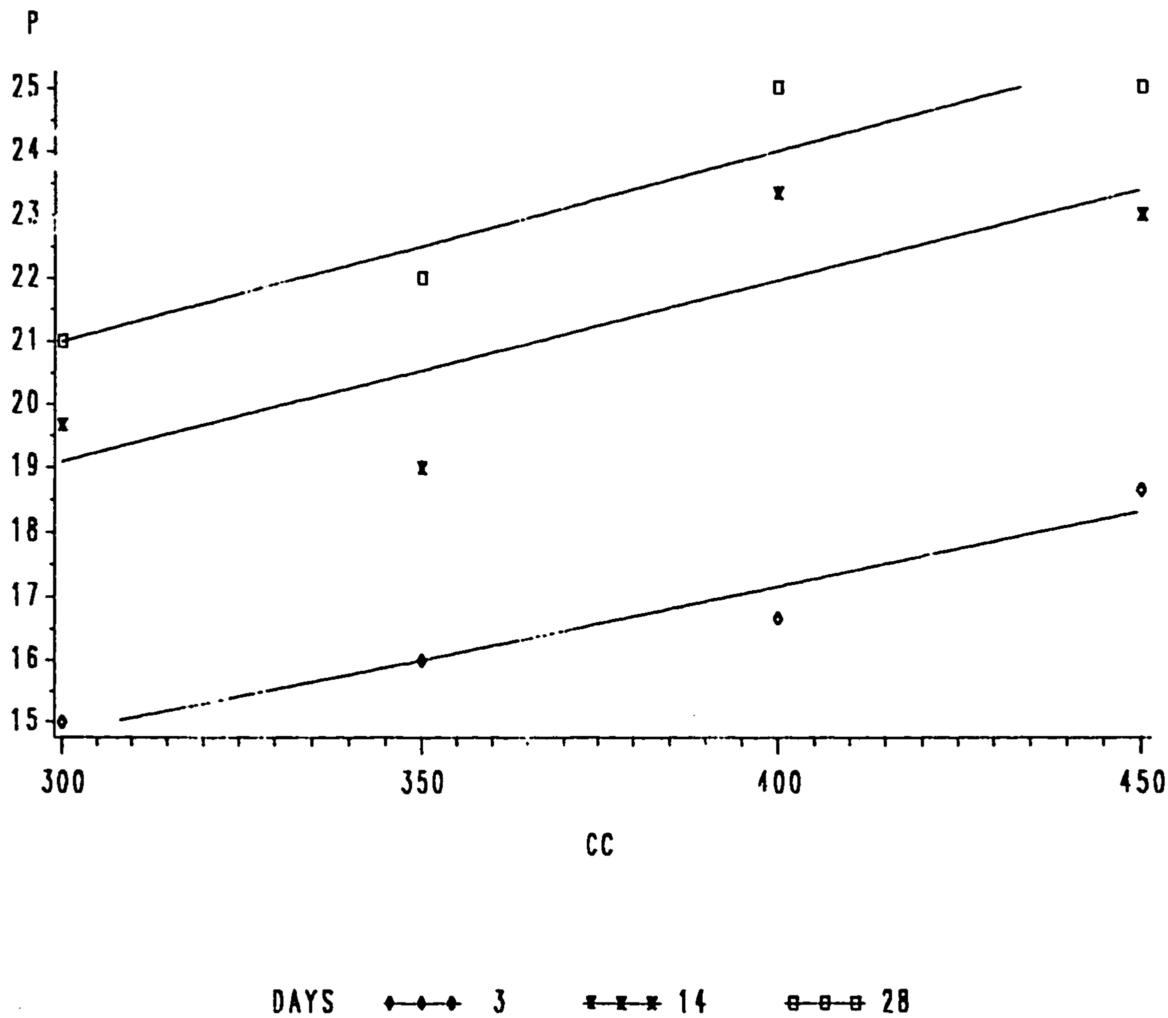


FIG. 4.5 RELATIONSHIP OF LOK AND CEMENT CONTENT FOR J. DHAHRAN

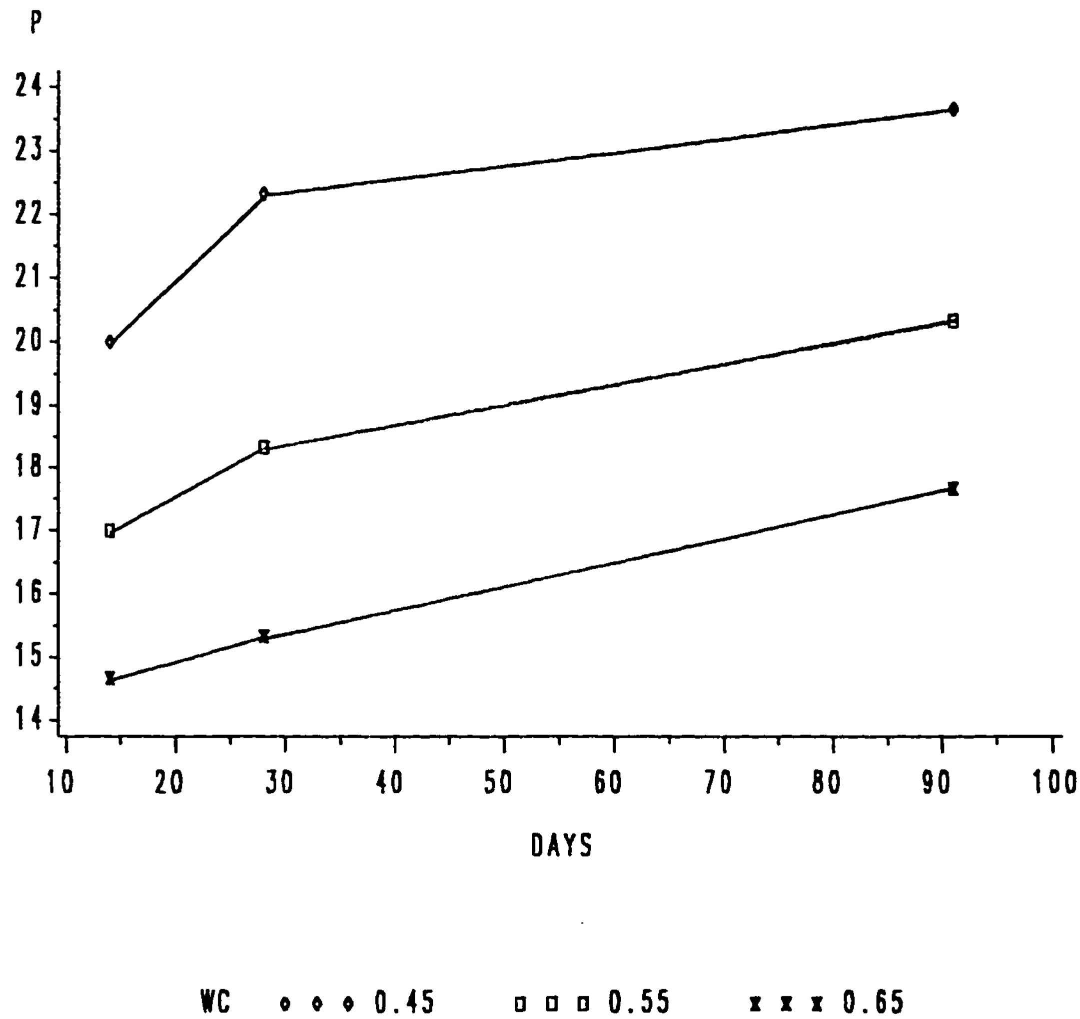
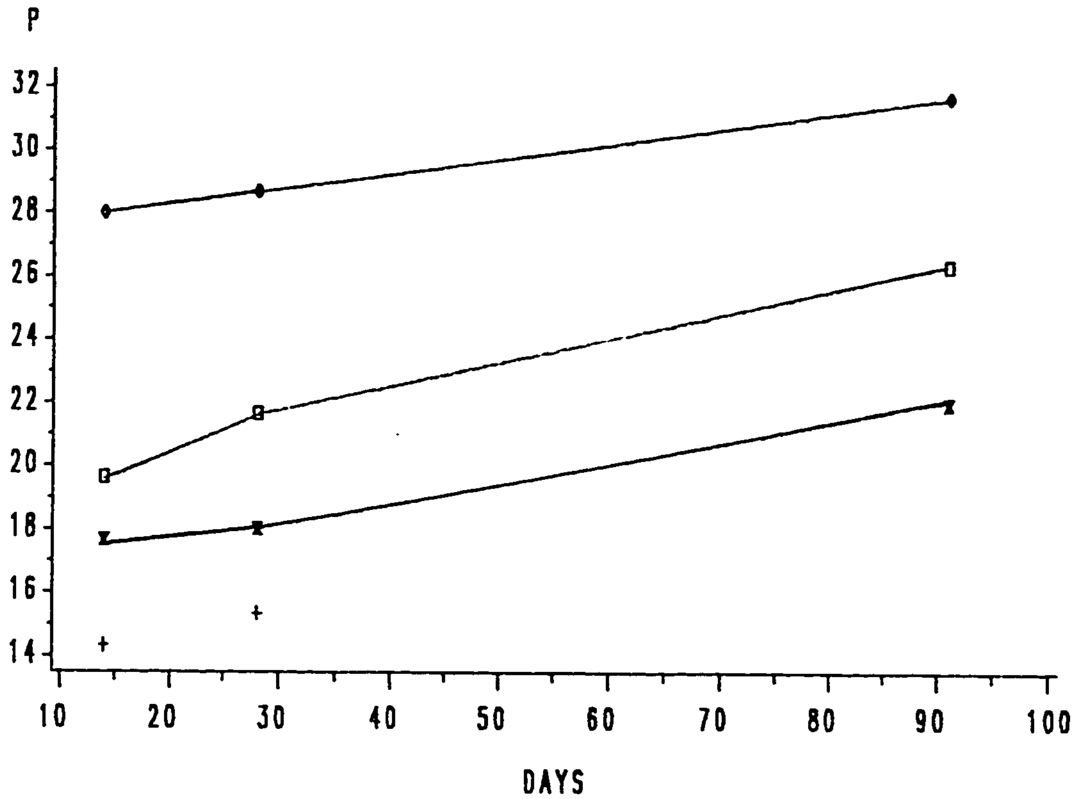


FIG. 4.6A RELATIONSHIP BETWEEN CAPO STRENGTH AND AGE FOR J. DH., CC=300



WC ◇ ◇ ◇ 0.45 □ □ □ 0.55 ⧗ ⧗ ⧗ 0.65 + + + 0.7

FIG. 4.6B: RELATIONSHIP BETWEEN CAPO STRENGTH AND AGE FOR J. DH., CC=400

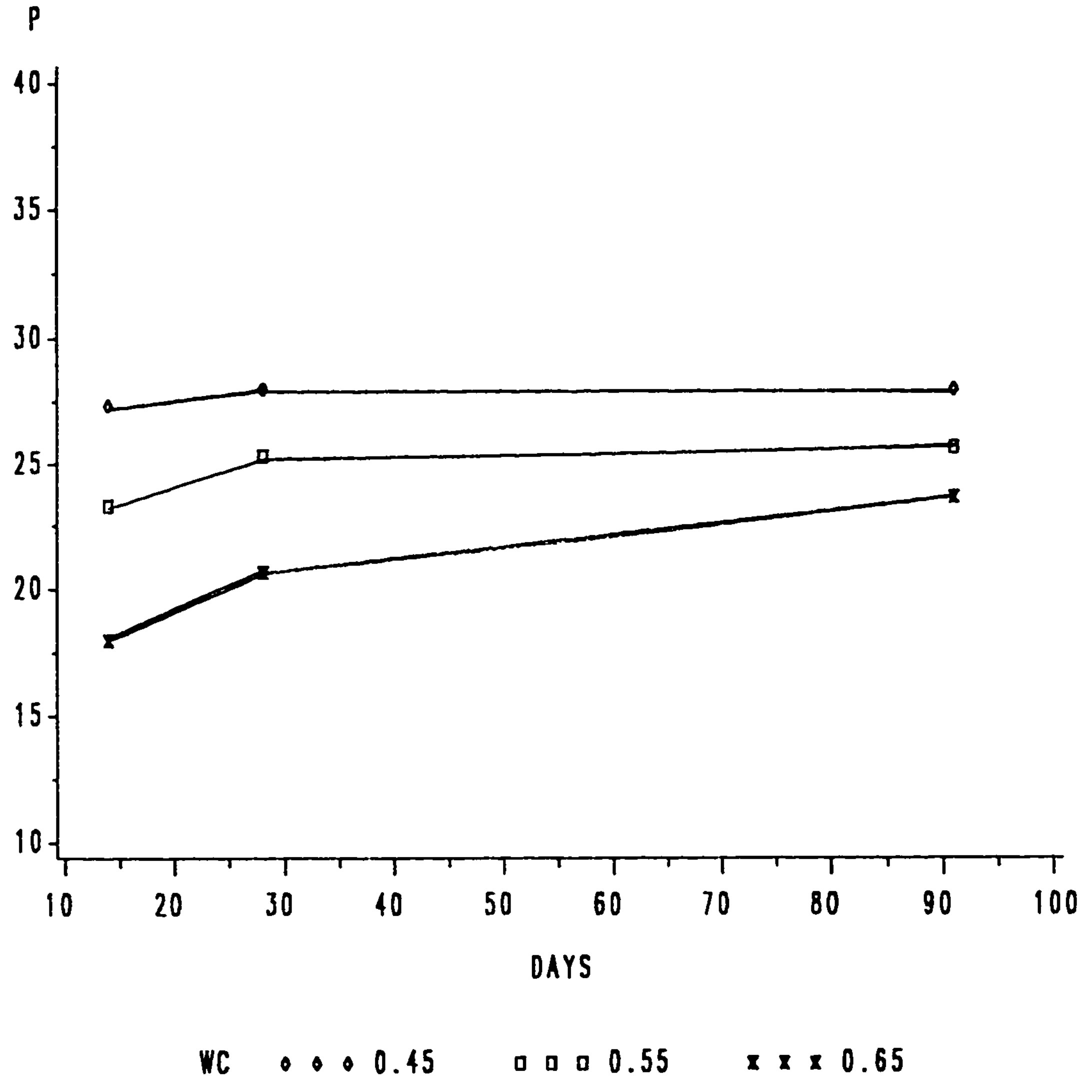


FIG. 4.7A: RELATIONSHIP BETWEEN CAPO STRENGTH AND AGE FOR ABU-HAD., CC=300

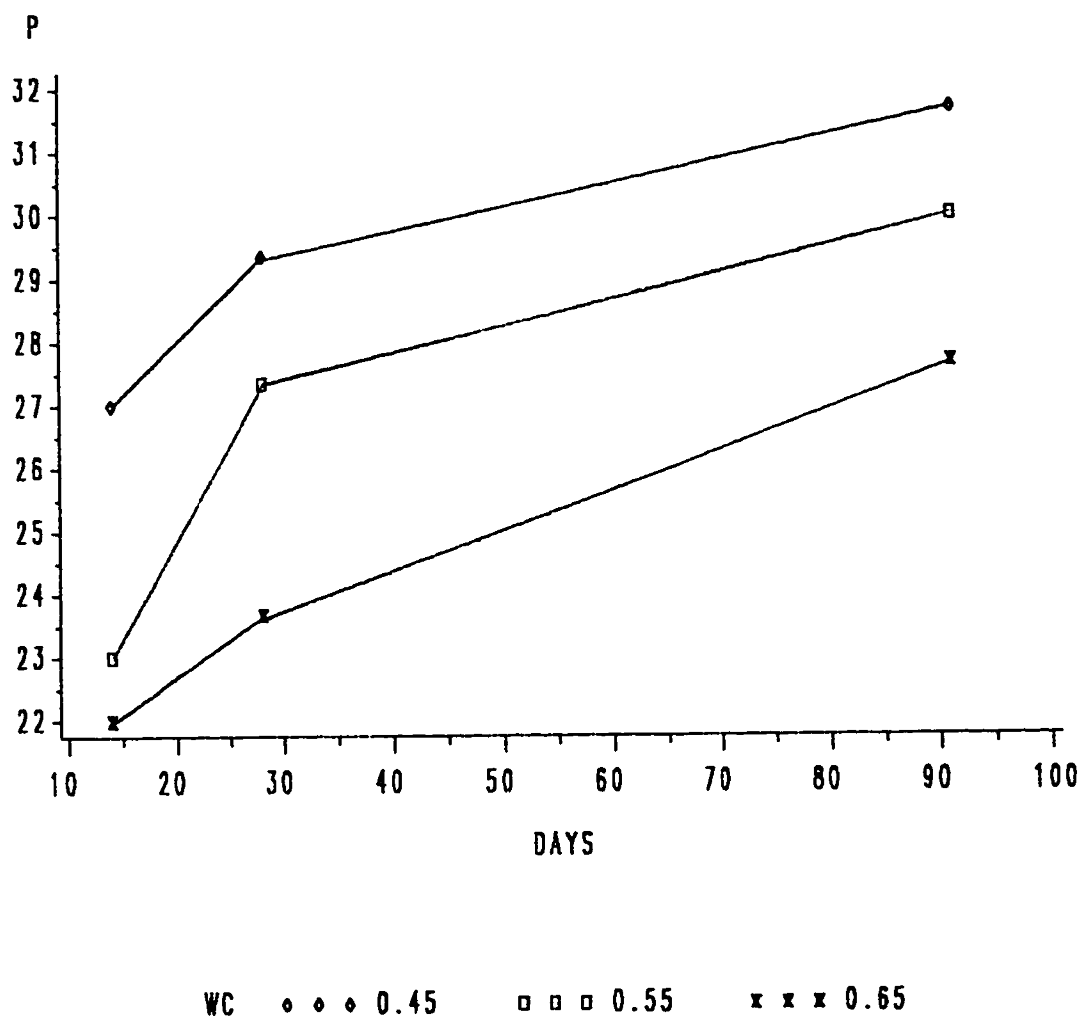
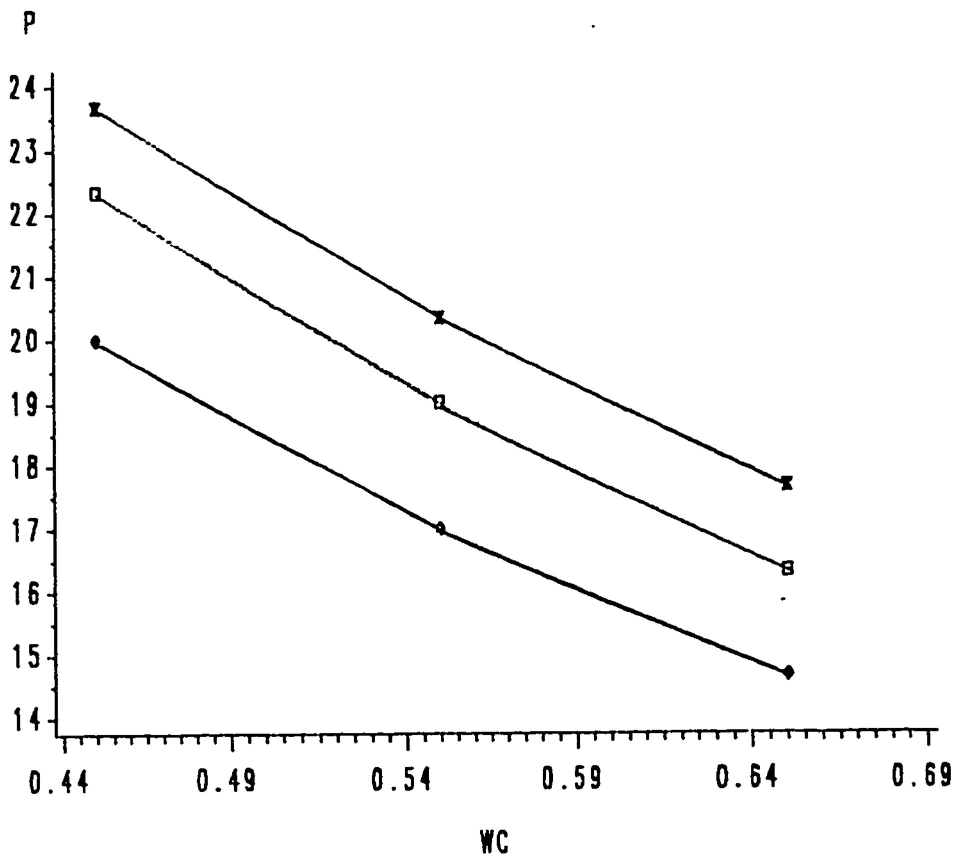


FIG. 4.7B: RELATIONSHIP BETWEEN CAPO STRENGTH AND AGE FOR ABU-HAD., CC=400



DAYS ◇ ◇ ◇ 14 □ □ □ 28 ⌧ ⌧ ⌧ 91

FIG. 4.8A RELATIONSHIP BETWEEN CAPO STRENGTH AND W/C FOR J. DH., CC=300

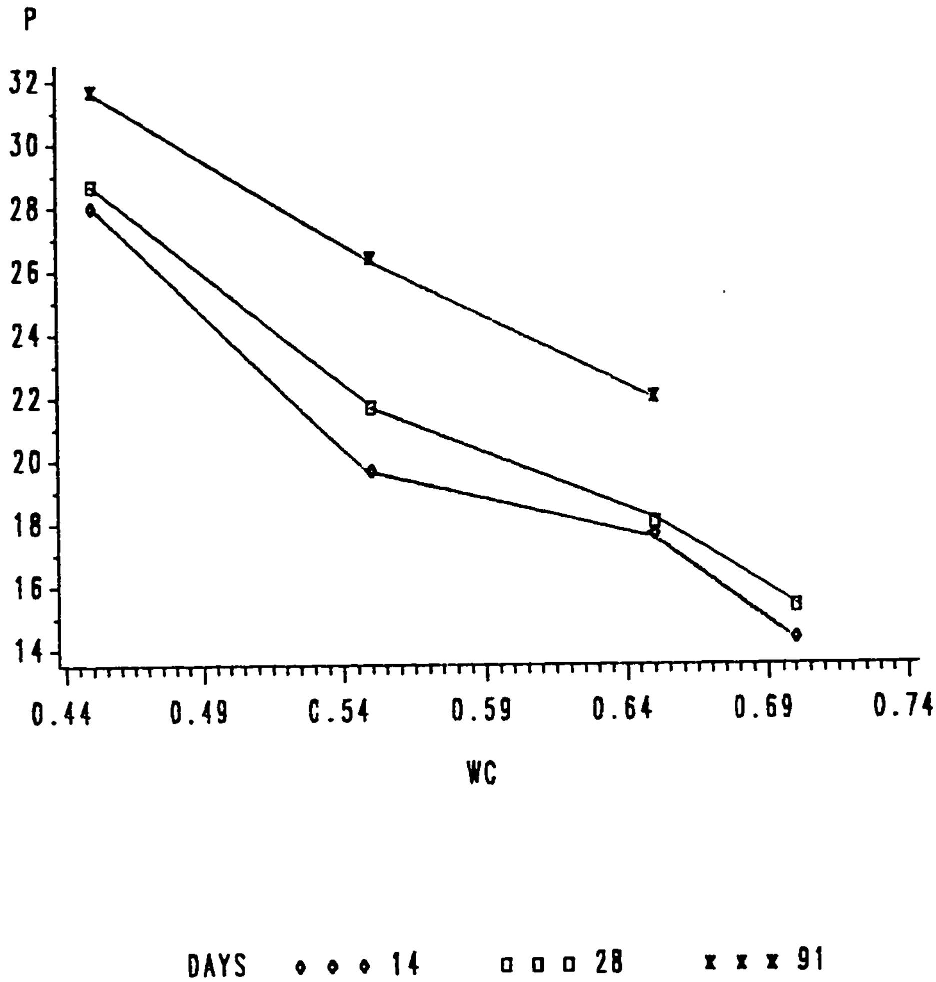
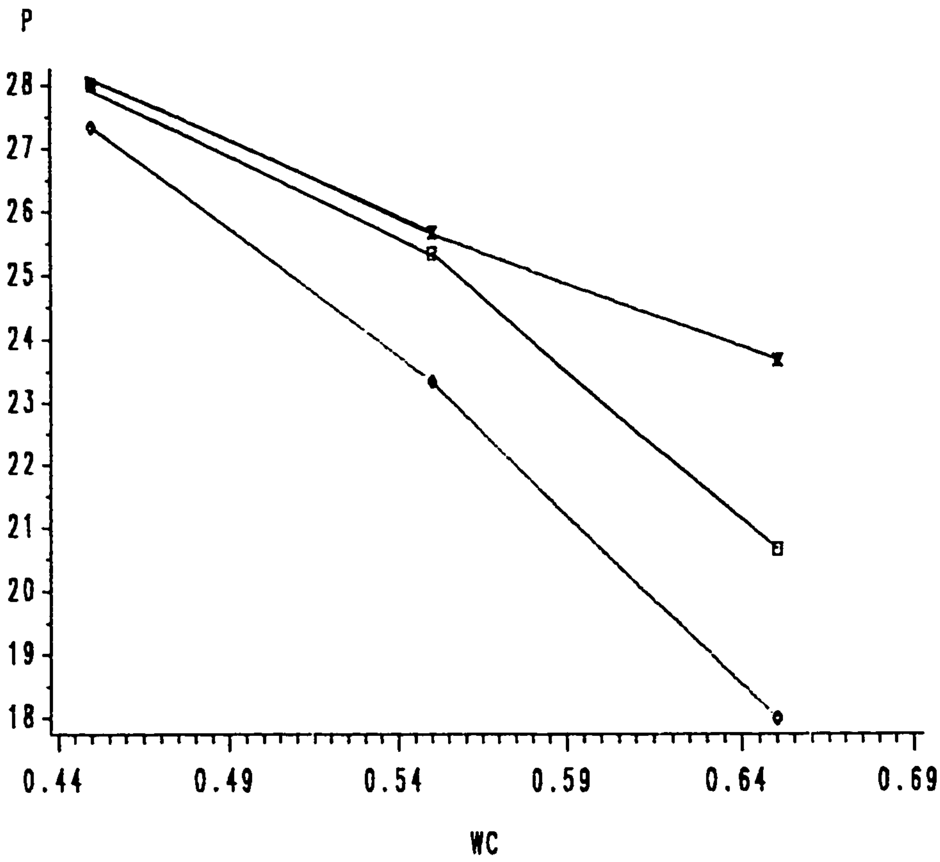


FIG. 4.8B: RELATIONSHIP BETWEEN CAPO STRENGTH AND W/C FOR J. DH., CC=400



DAYS ◇◇◇ 14 □□□ 28 ⌛⌛⌛ 91

FIG. 4.9A: RELATIONSHIP BETWEEN CAPO STRENGTH AND W/C FOR ABU-HAD., CC=300

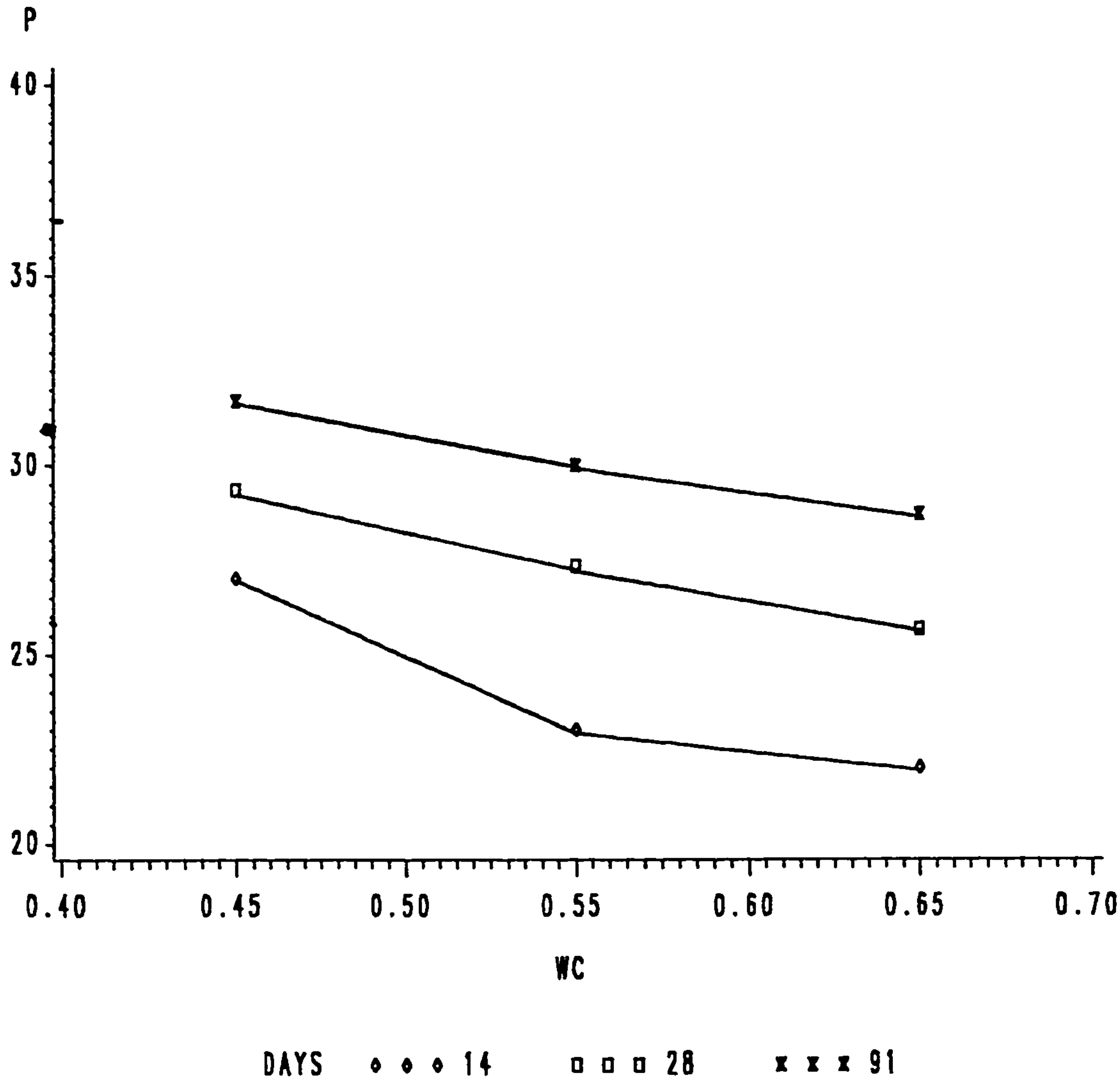


FIG. 4.9B: RELATIONSHIP BETWEEN CAPO STRENGTH AND W/C FOR ABU-H., CC=400

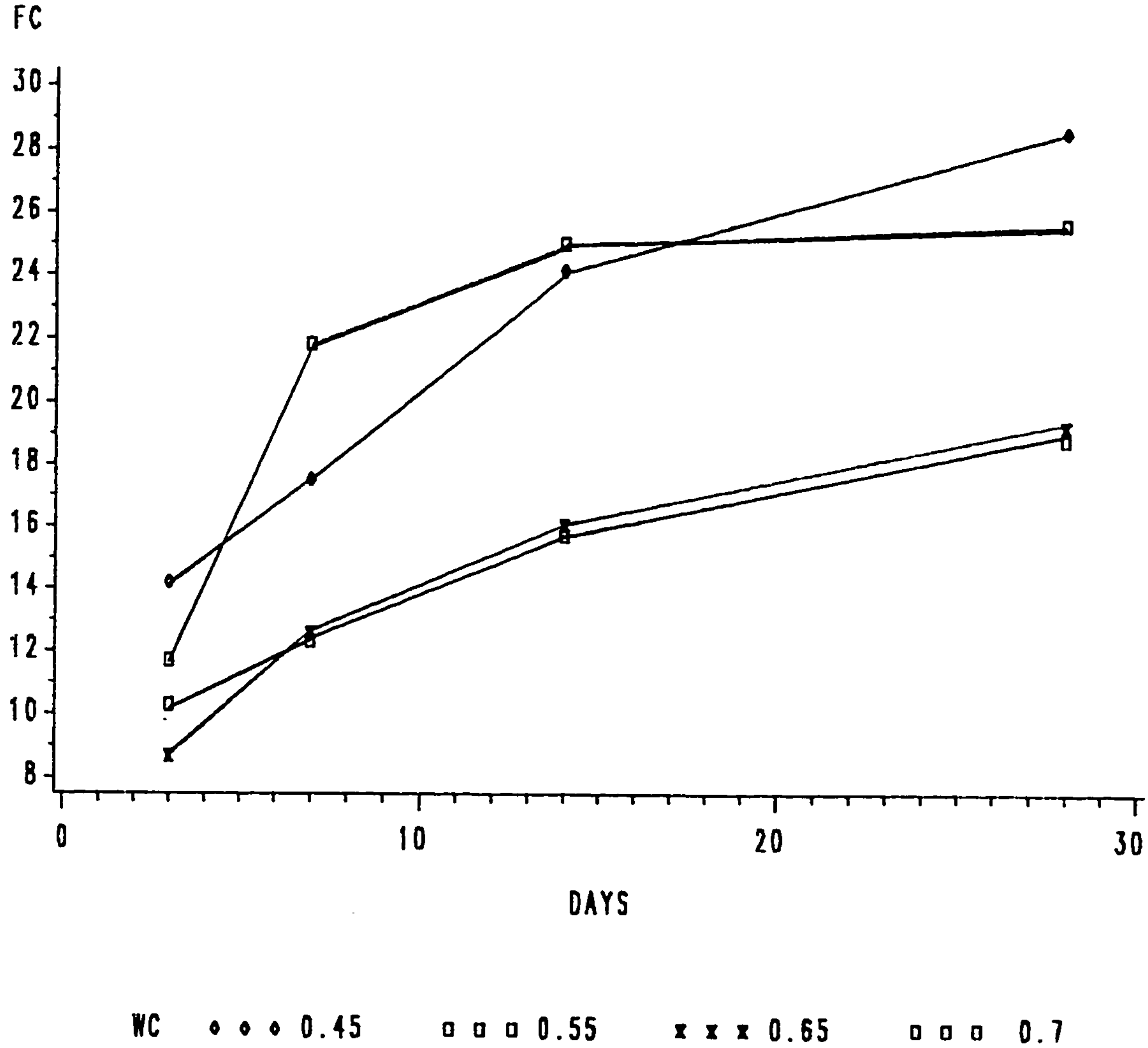


FIG. 4.10A: RELATIONSHIP OF COMPRESSIVE-STRENGTH AND AGE FOR J. DH., CC=300

3L

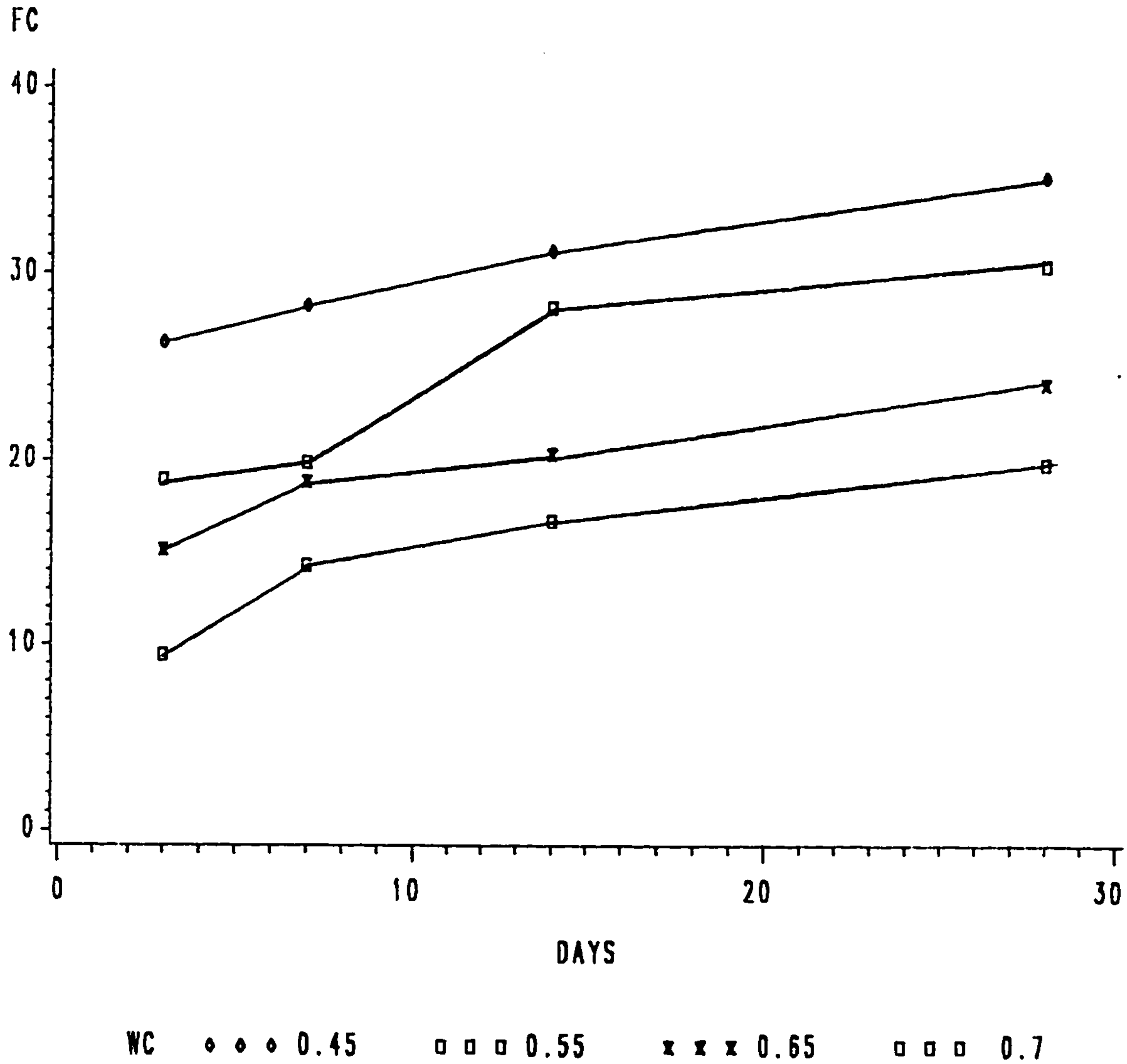


FIG. 4.10B: RELATIONSHIP OF COMPRESSIVE-STRENGTH AND AGE FOR J. DH., CC=400

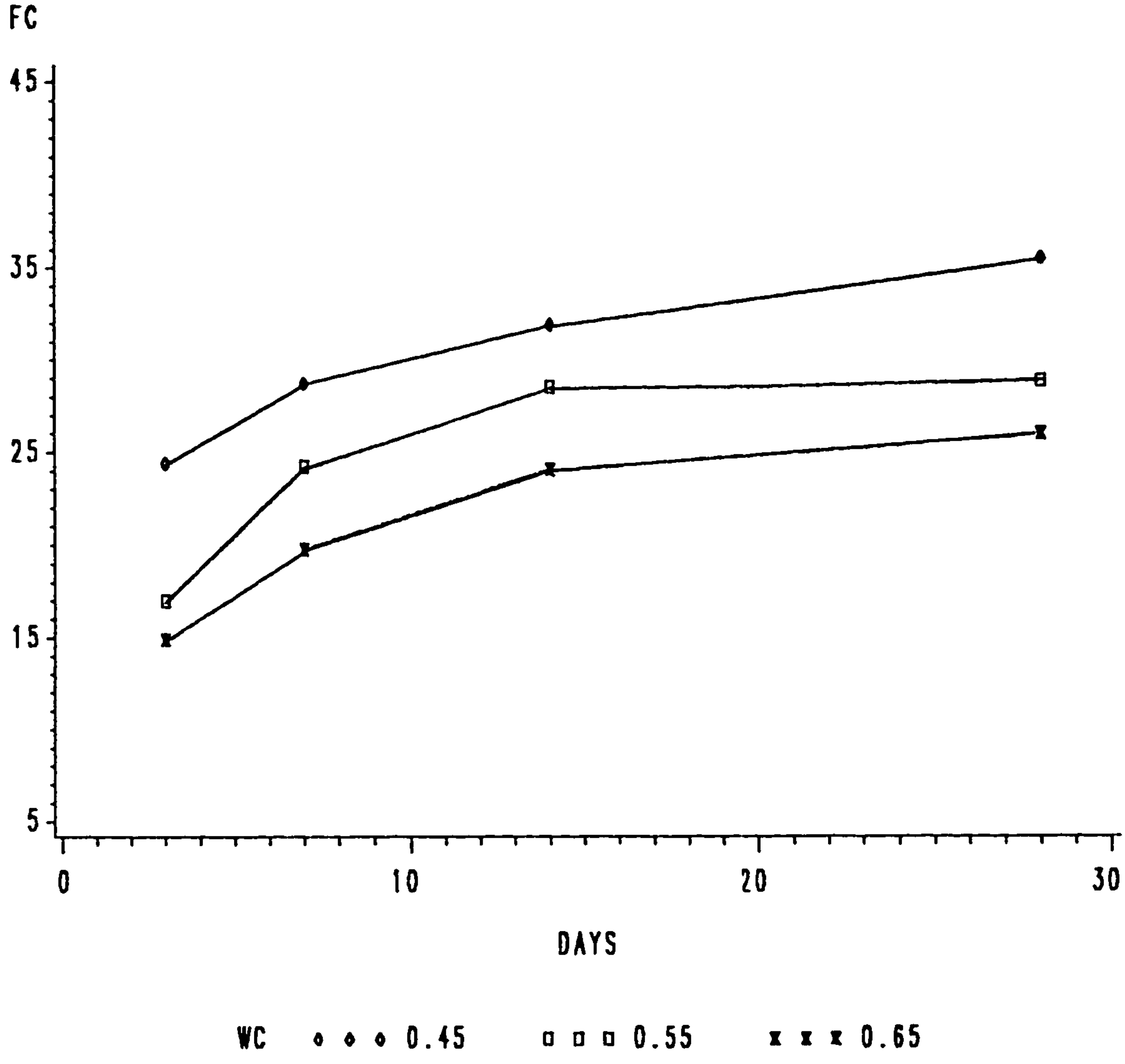


FIG. 4.11A: RELATIONSHIP OF COMPRESSIVE STRENGTH AND AGE FOR ABU-HAD. , CC= 300

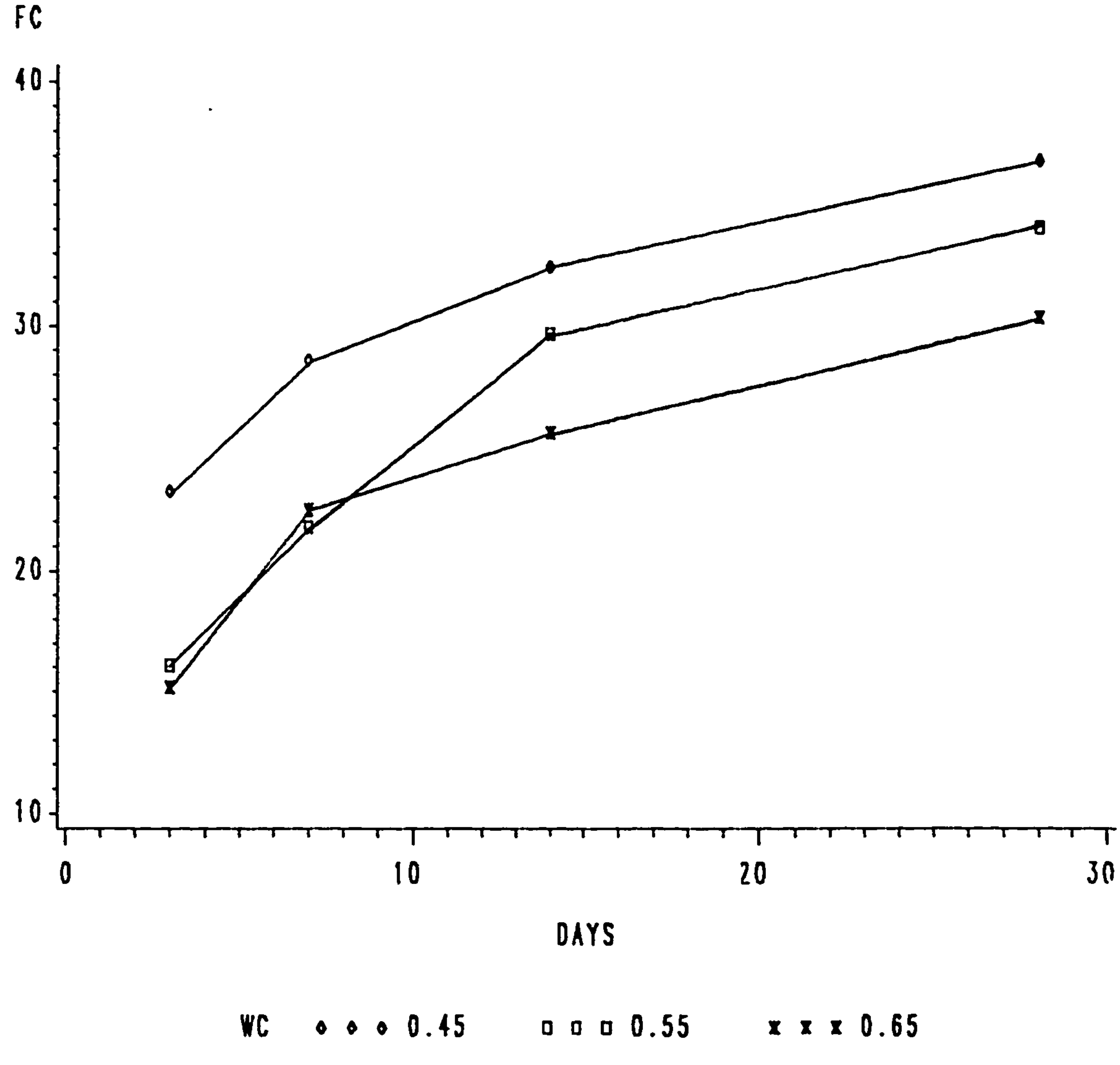


FIG. 4.11B: RELATIONSHIP OF COMPRESSIVE STRENGTH AND AGE FOR ABU-HAD. , CC= 400

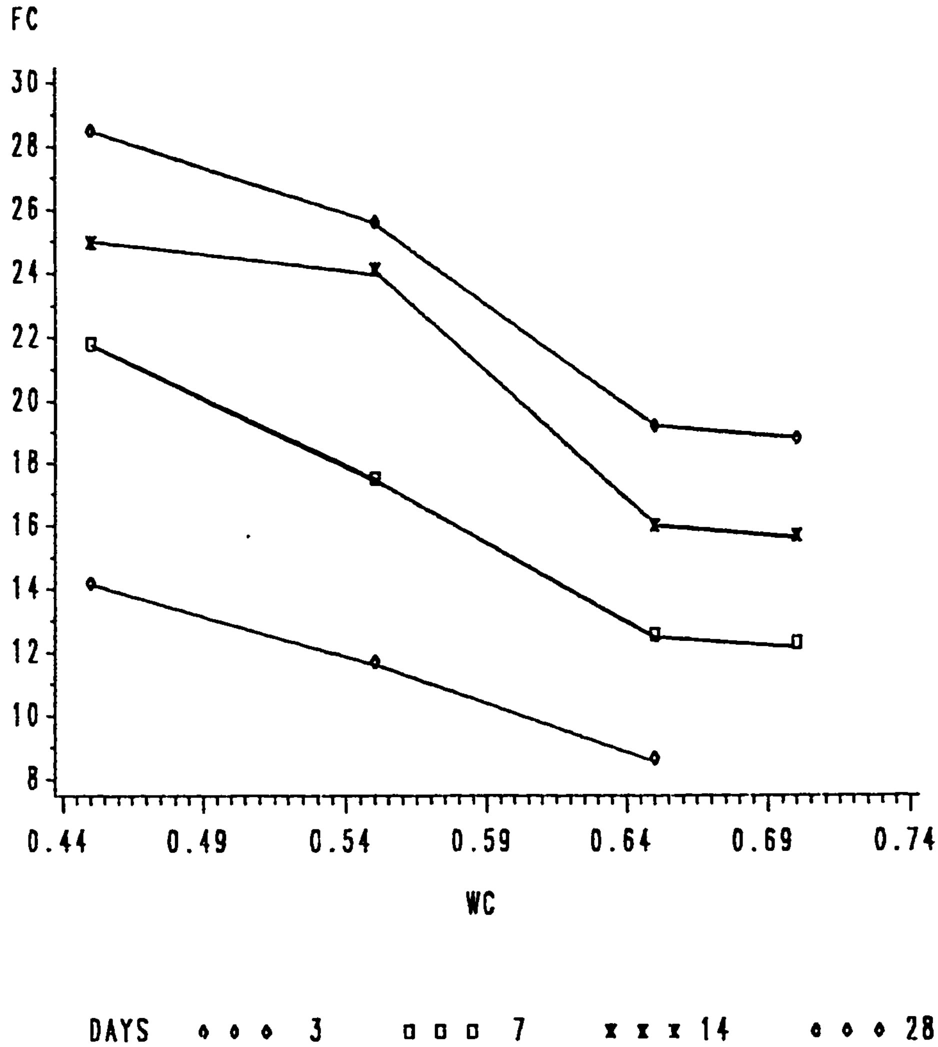


FIG. 4.12A: RELATIONSHIP OF COMPRESSIVE STRENGTH AND W/C FOR J. DH., CC=300

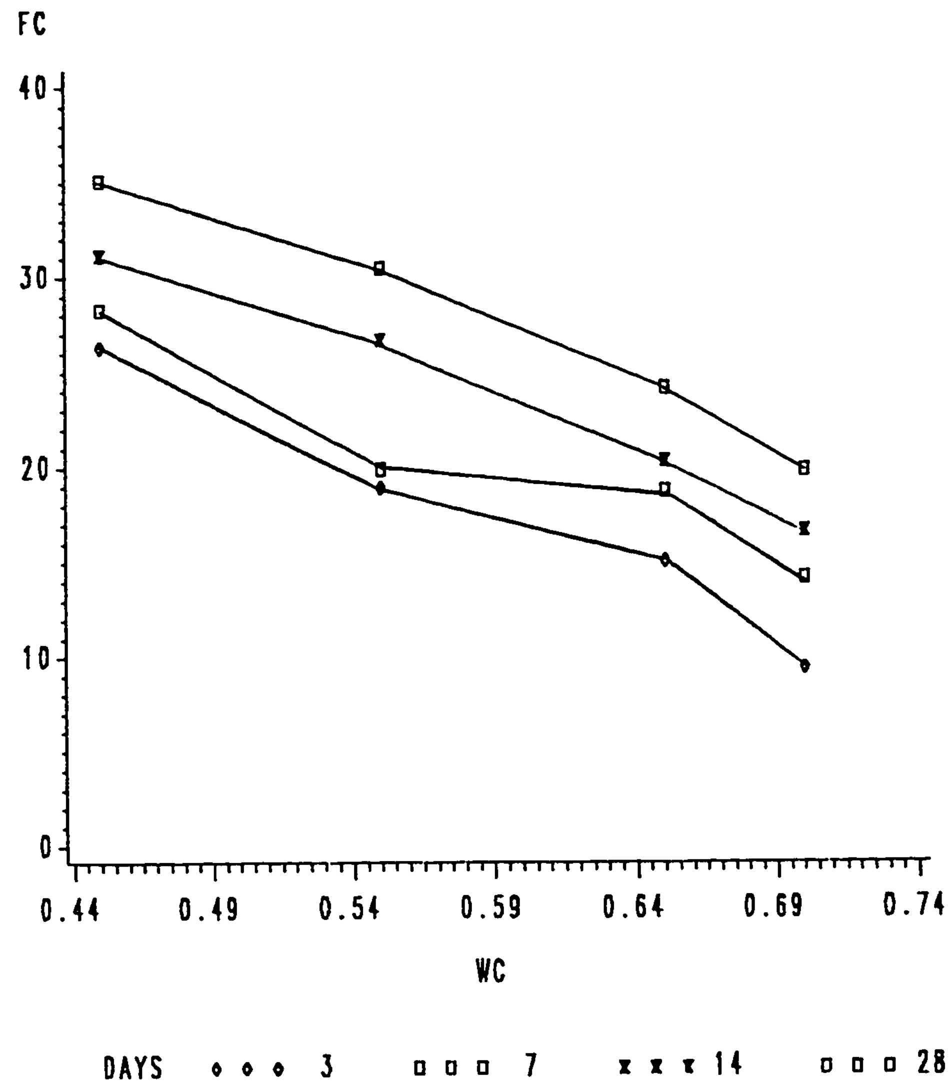


FIG. 4.12B:RELATIONSHIP OF COMPRESSIVESTRENGTH AND W/C FOR J. DH.,CC=400

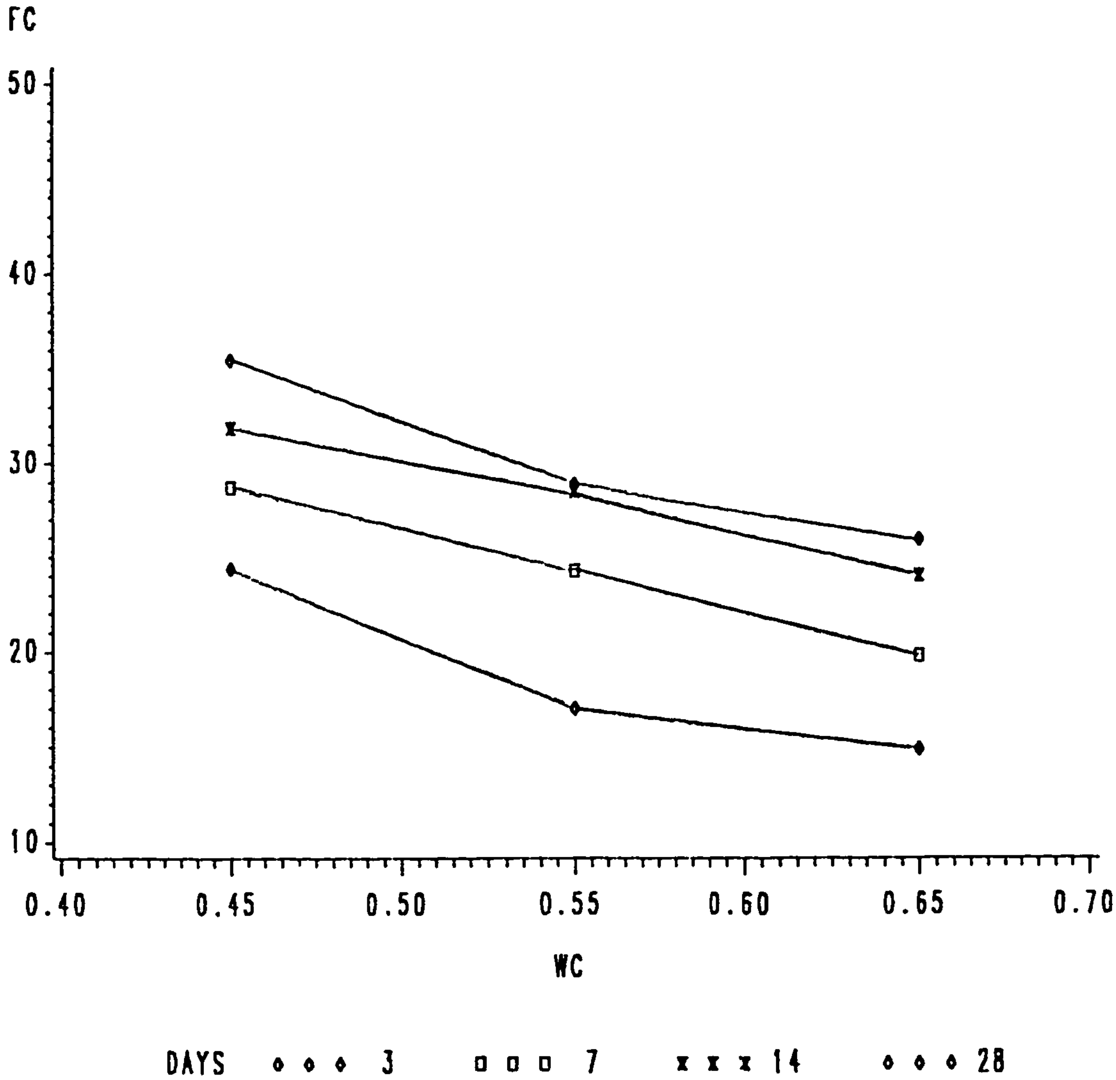


FIG. 4.13A: RELATIONSHIP OF COMPRESSIVE STRENGTH AND W/C FOR ABU-HAD., CC=300

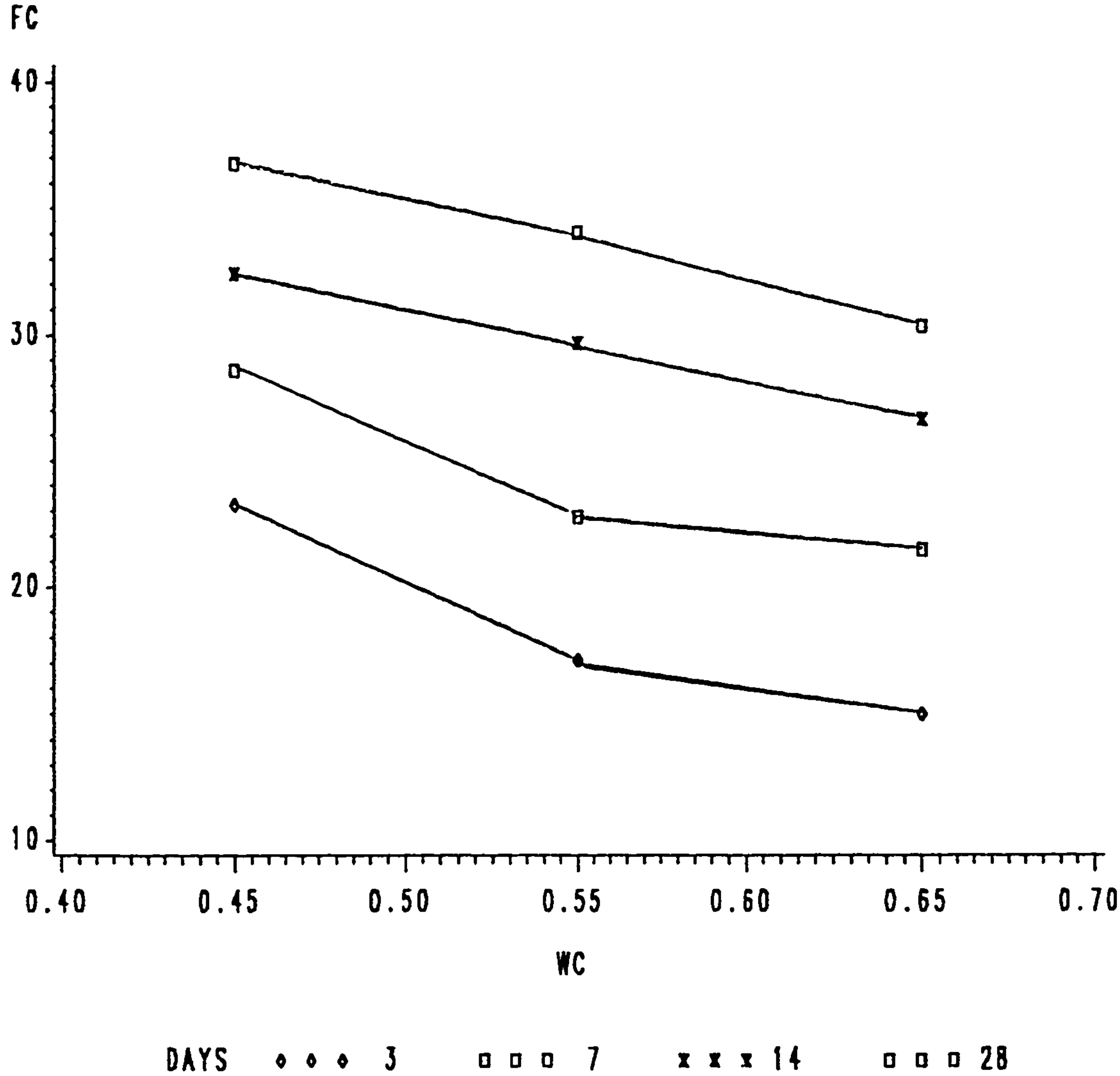


FIG. 4.13B: RELATIONSHIP OF COMPRESSIVE STRENGTH AND W/C FOR ABU-H.,CC=400

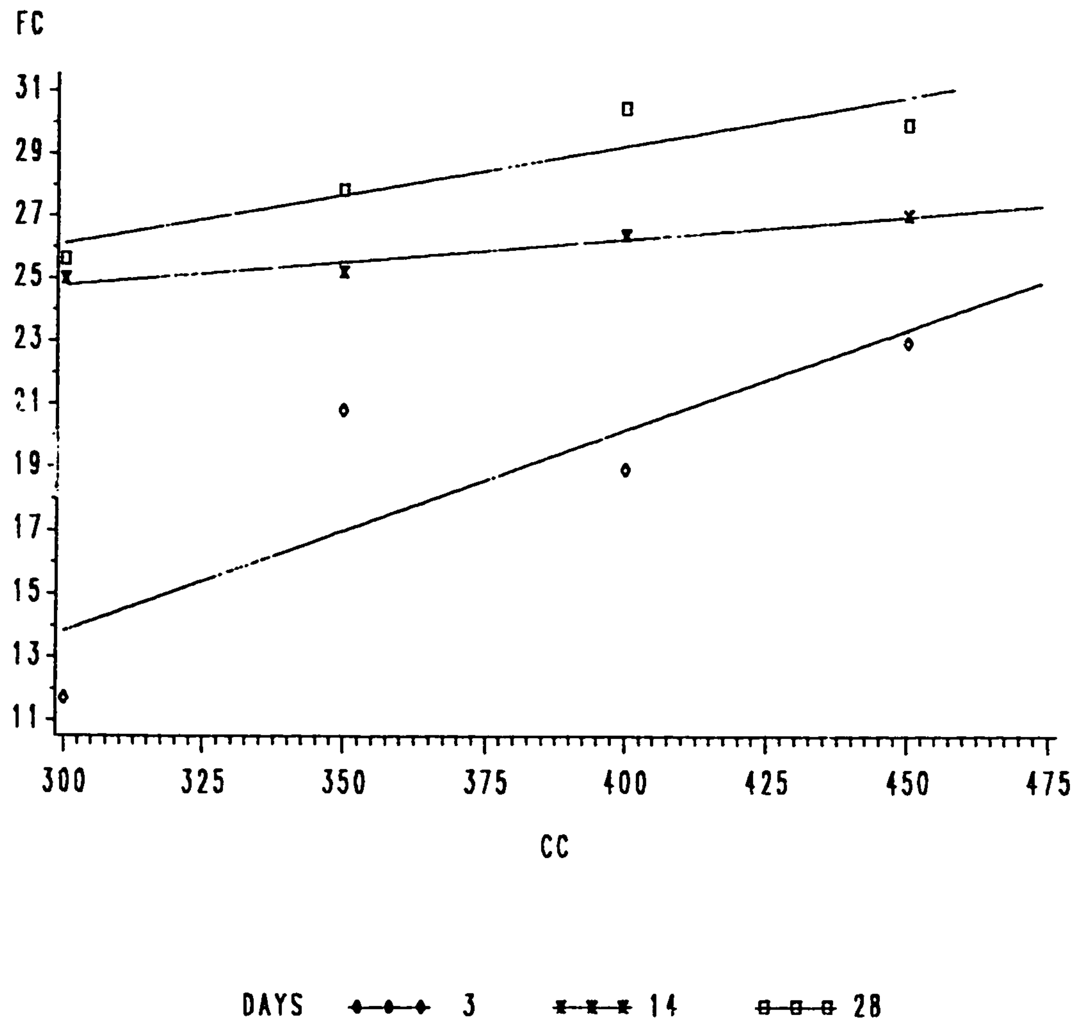
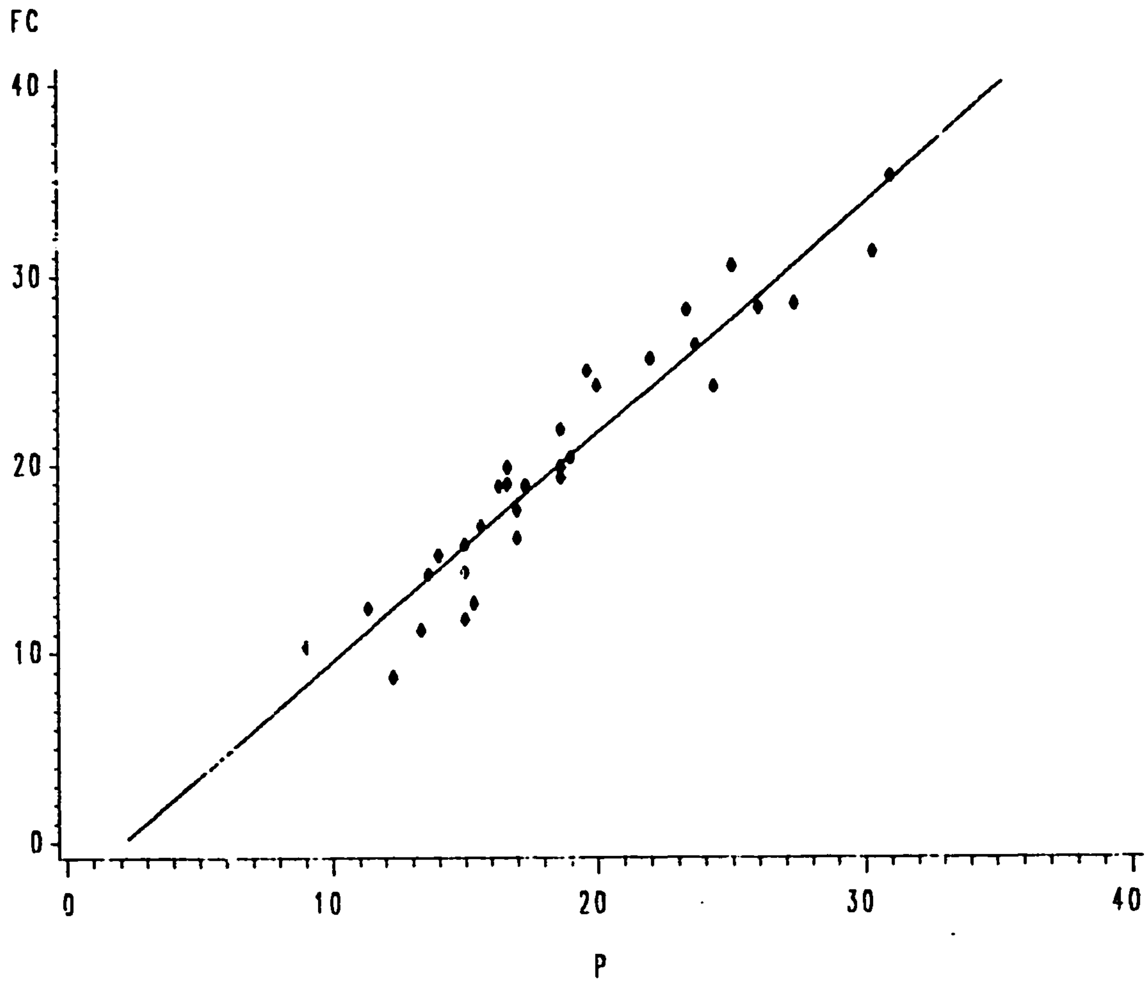
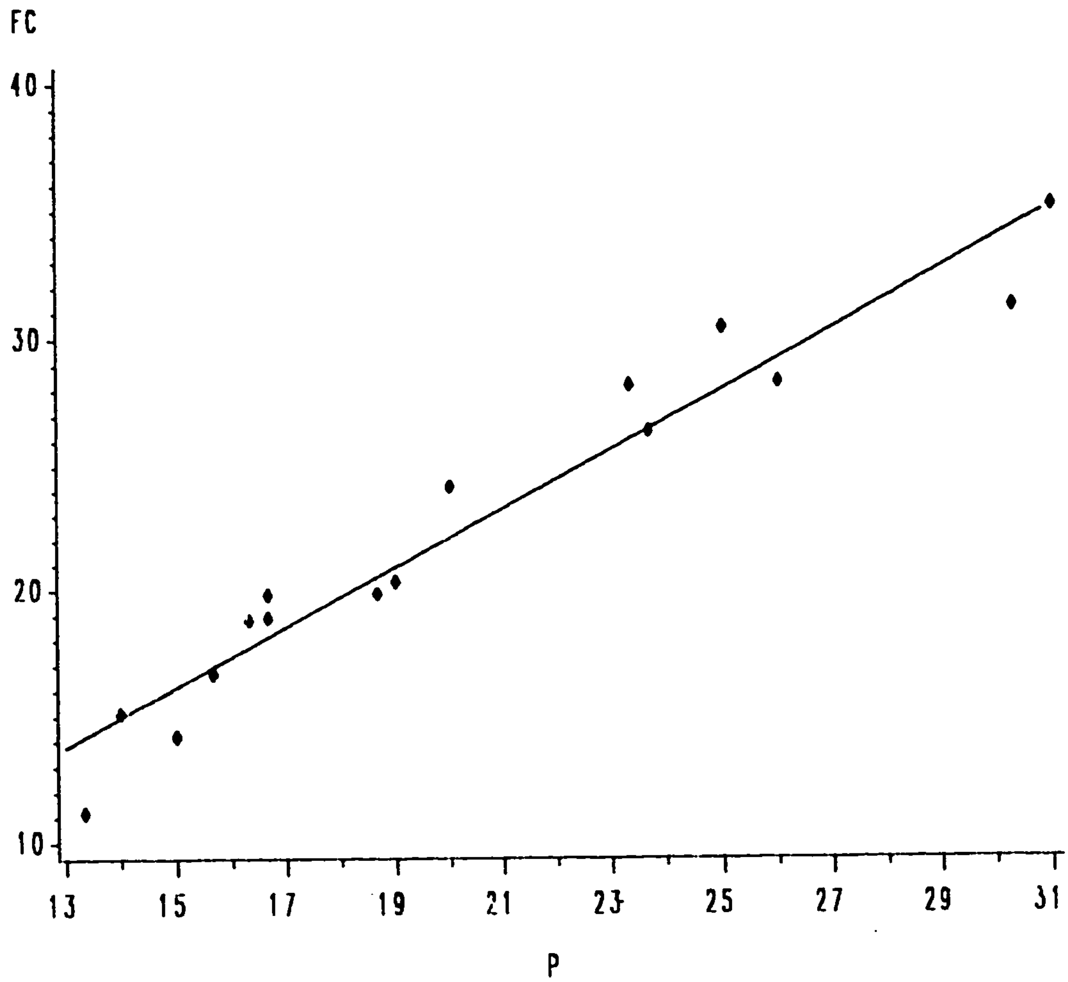


FIG. 4.14: RELATIONSHIP OF COMPRESSIVE STRENGTH AND CEMENT CONTENT FOR J. DH



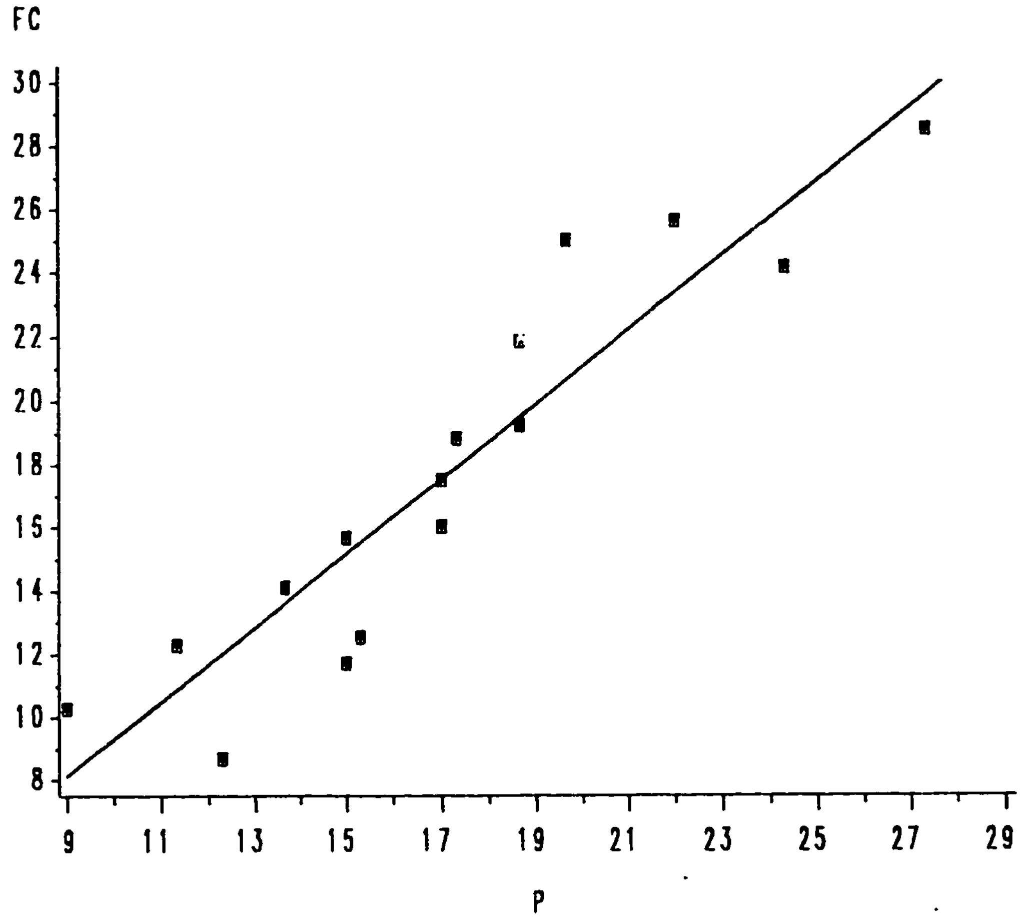
FC=-2.60 +1.21 P

FIG. 4.15A: RELATIONSHIP BETWEEN COMPRESSIVE AND LOK STRENGTH FOR DH.



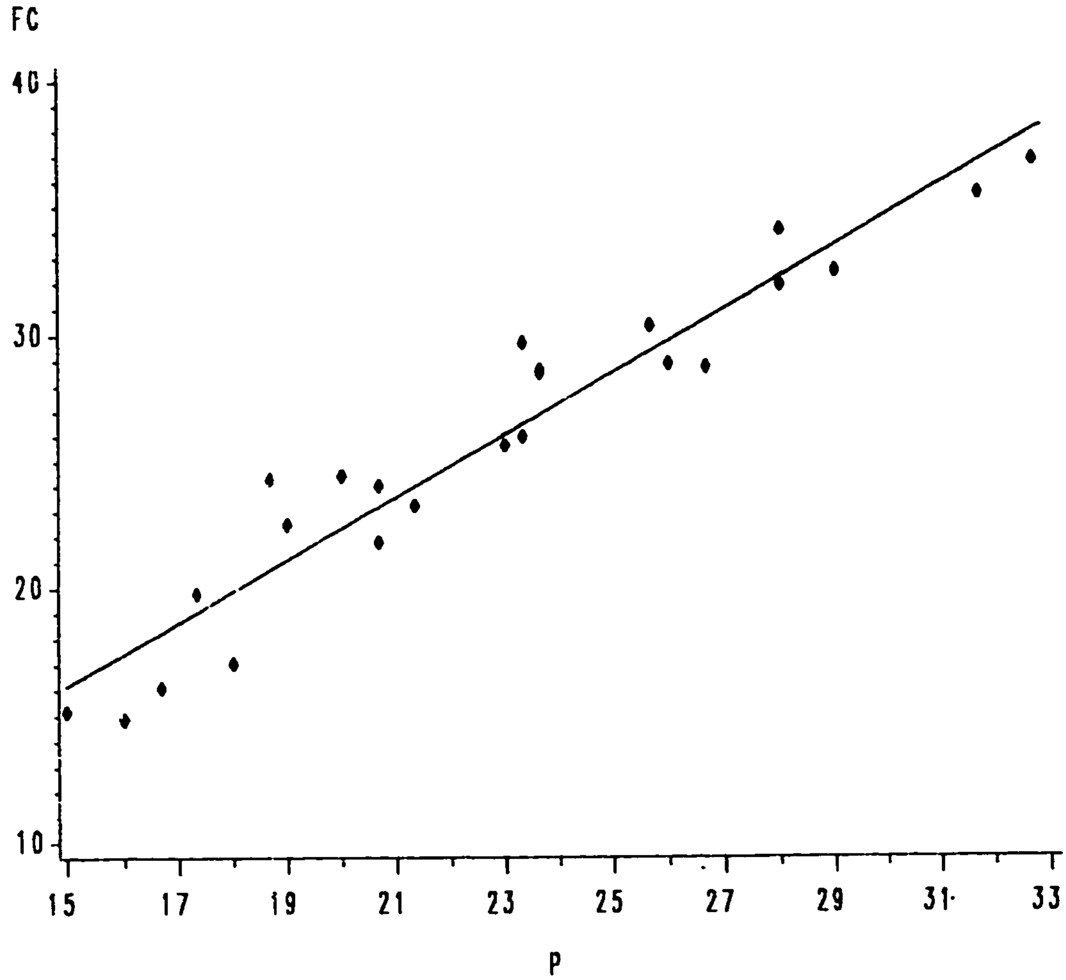
FC =-1.67+1.19 P

FIG. 4.15B: RELATIONSHIP BETWEEN COMPRESSIVE AND LOK STRENGTH FOR DH., CC=400

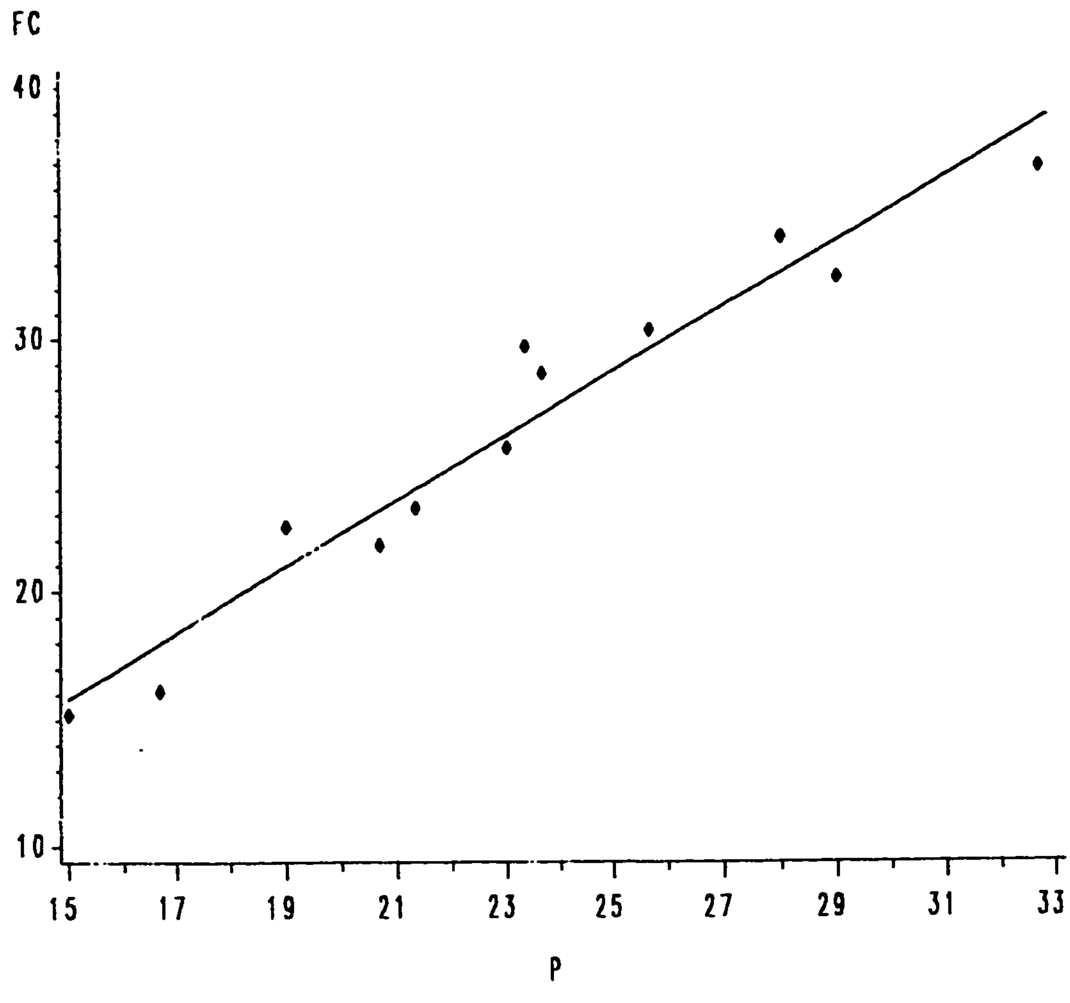


FC =-2.42 +1.17 P

FIG. 4.15C: RELATIONSHIP BETWEEN COMPRESSIVE AND LOK STRENGTH FOR DH., CC=300

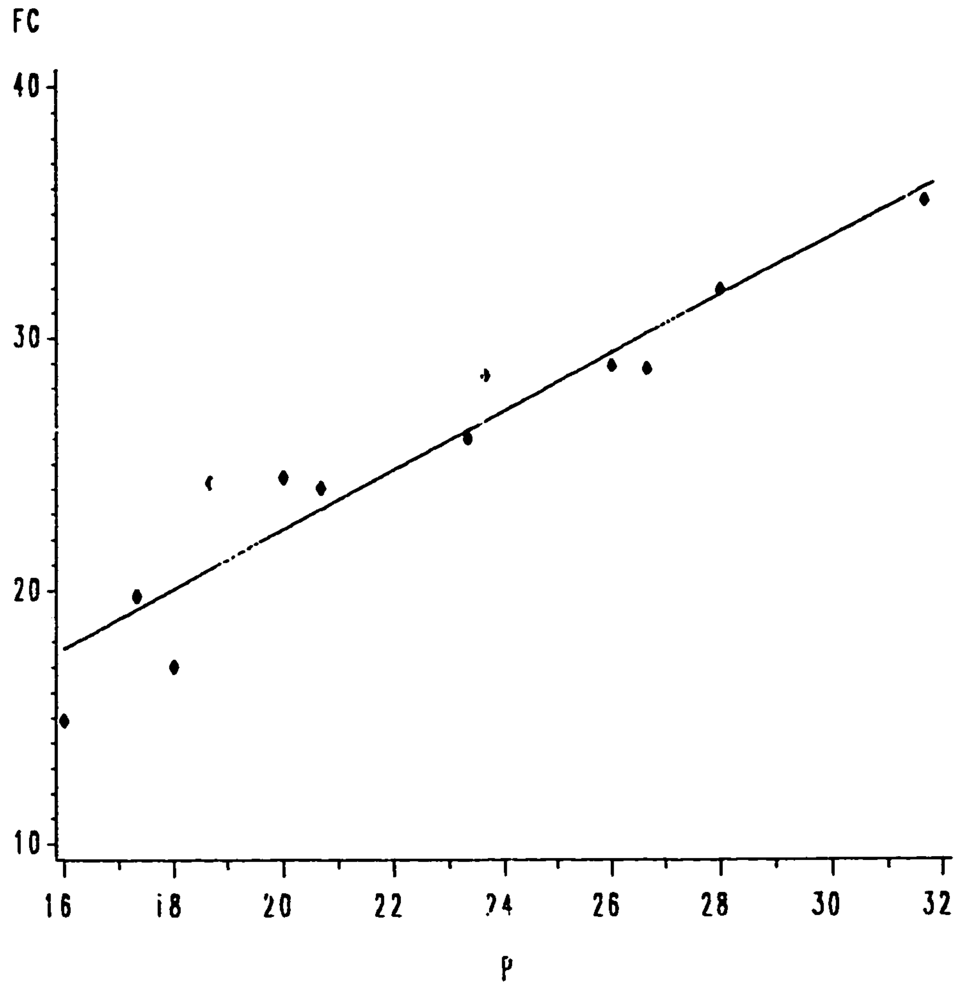


FC=-2.266+1.23 P
FIG. 4.16A: RELATIONSHIP BETWEEN COMPRESSIVE AND LOK STRENGTH FOR ABU-H.



FC =-3.49 +1.29 P

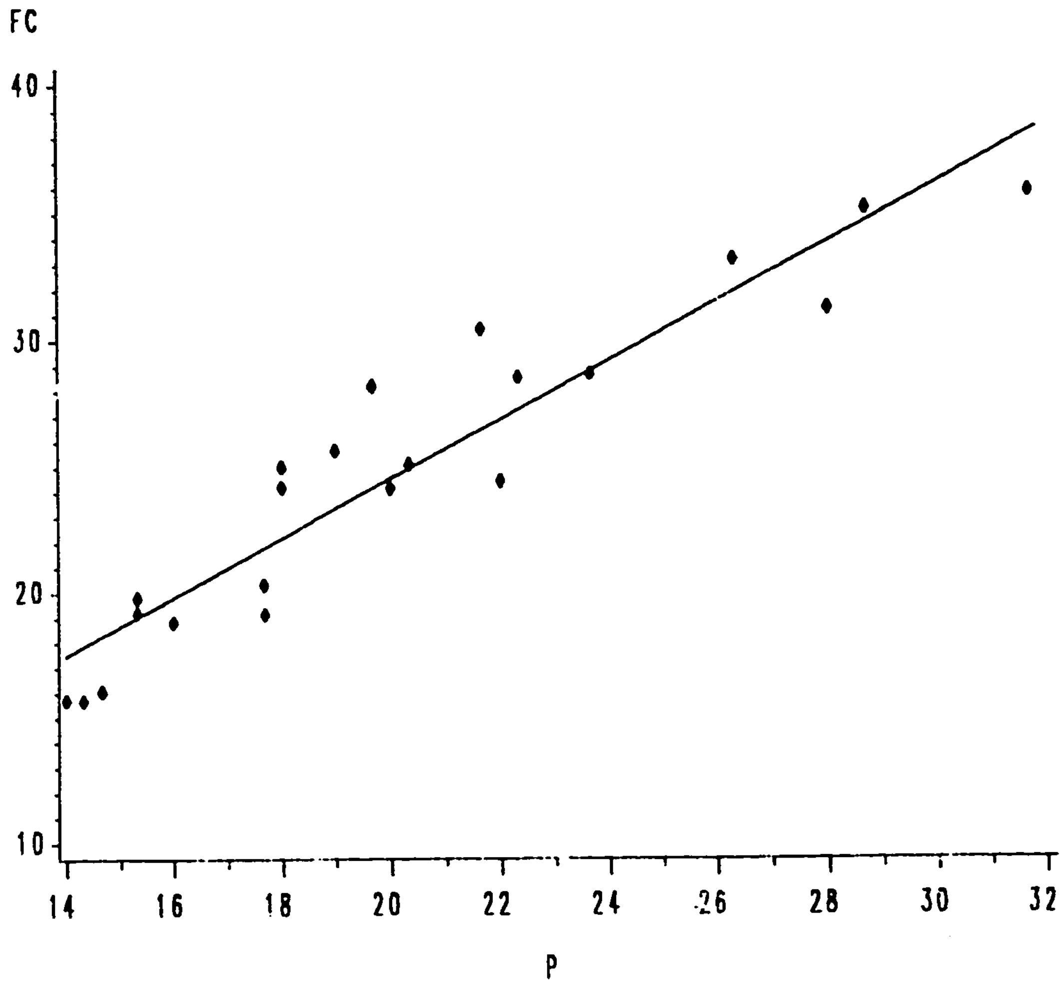
FIG. 4.16B: RELATIONSHIP BETWEEN COMPRESSIVE AND LOK STRENGTH FOR ABU-H., CC=400



FC =-.854 +1.162 P

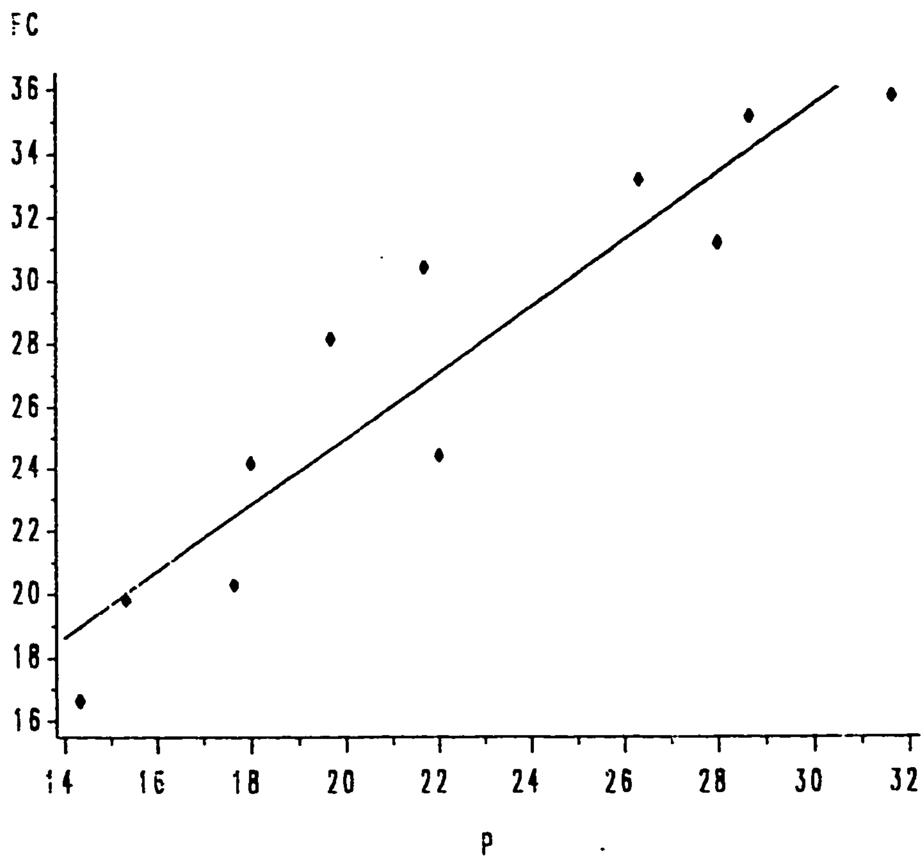
FIG. 4.16C: RELATIONSHIP BETWEEN COMPRESSIVE AND LOK STRENGTH FOR ABU-H., CC=300

3L



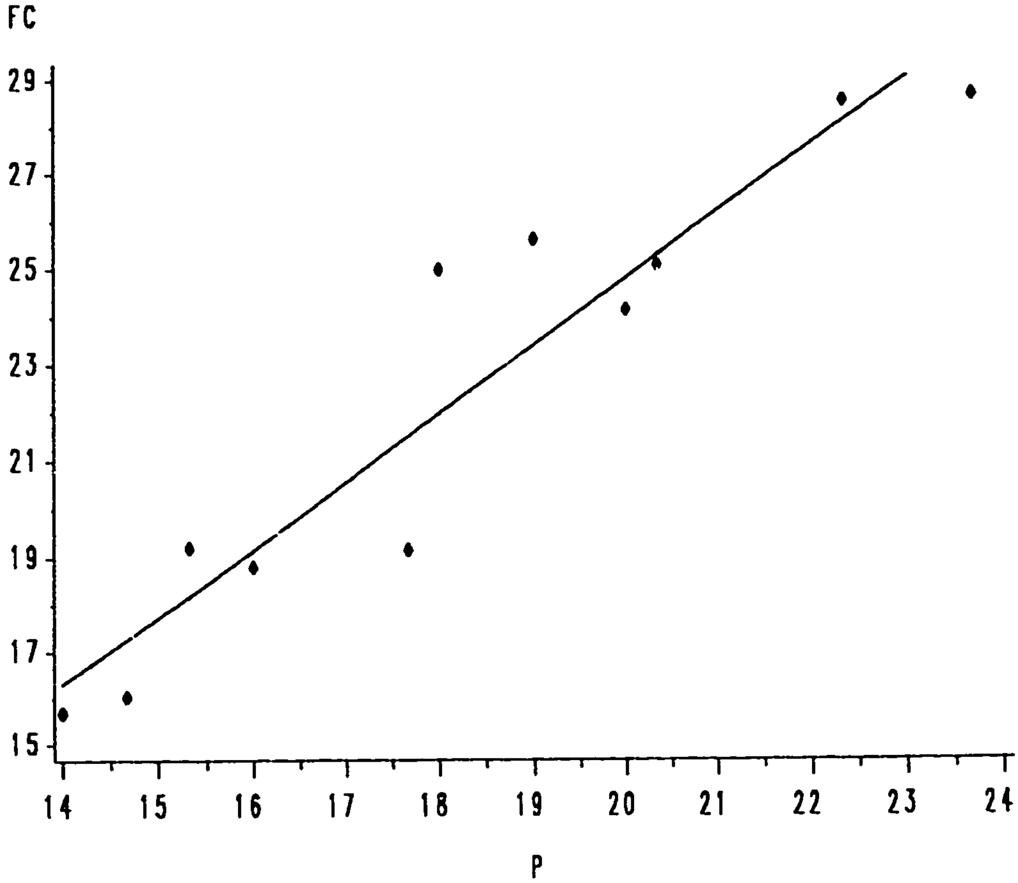
FC=1.18 +1.17 P

FIG. 4.17A: RELATIONSHIP OF COMPRESSIVE AND CAPO STRENGTH FOR J. DH



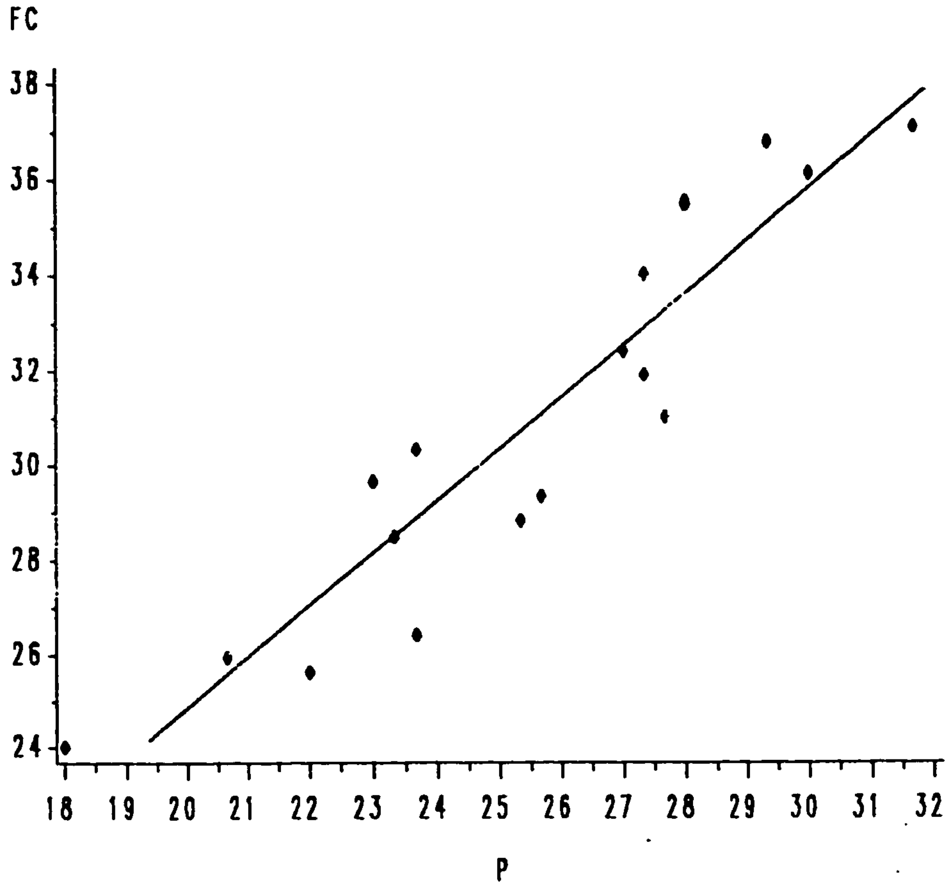
FC =3.90+1.053 P

FIG. 4.17B: RELATIONSHIP OF COMPRESSIVE AND CAPO STRENGTH FOR J.DH., CC=400



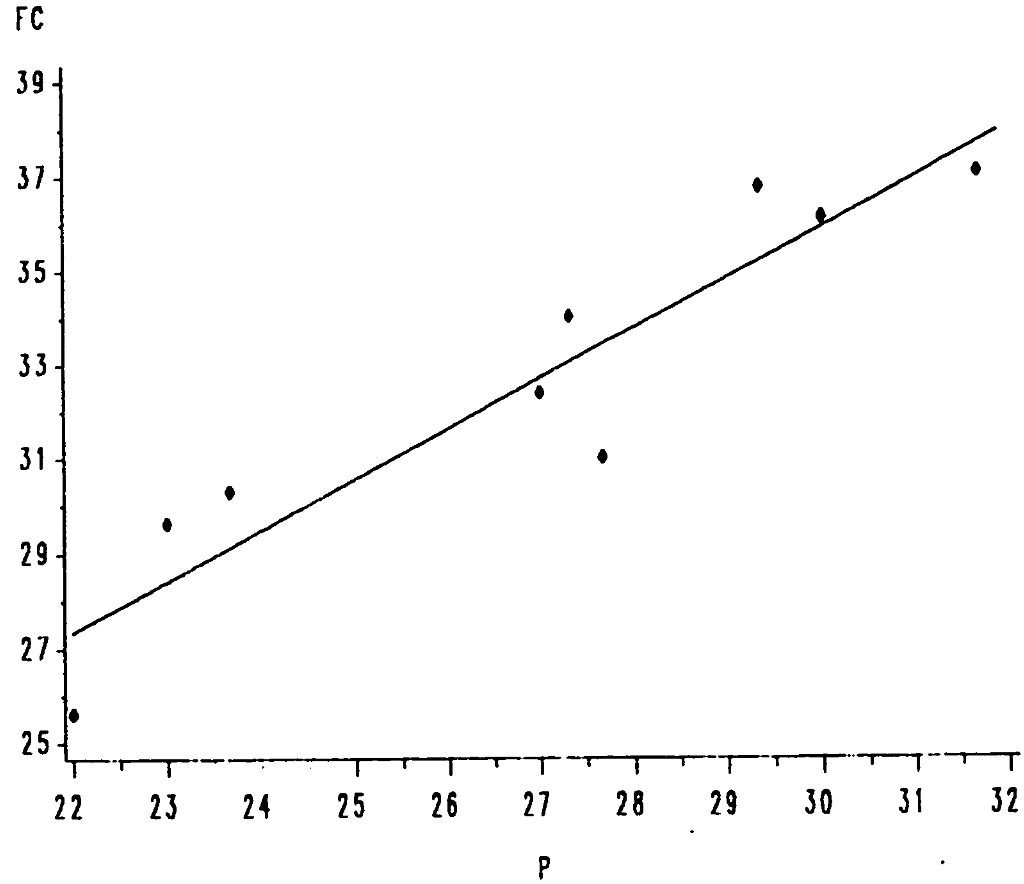
FC=-3.44 +1.41 P

FIG. 4.17C: RELATIONSHIP OF COMPRESSIVE AND CAPO STRENGTH FOR DH., CC=300



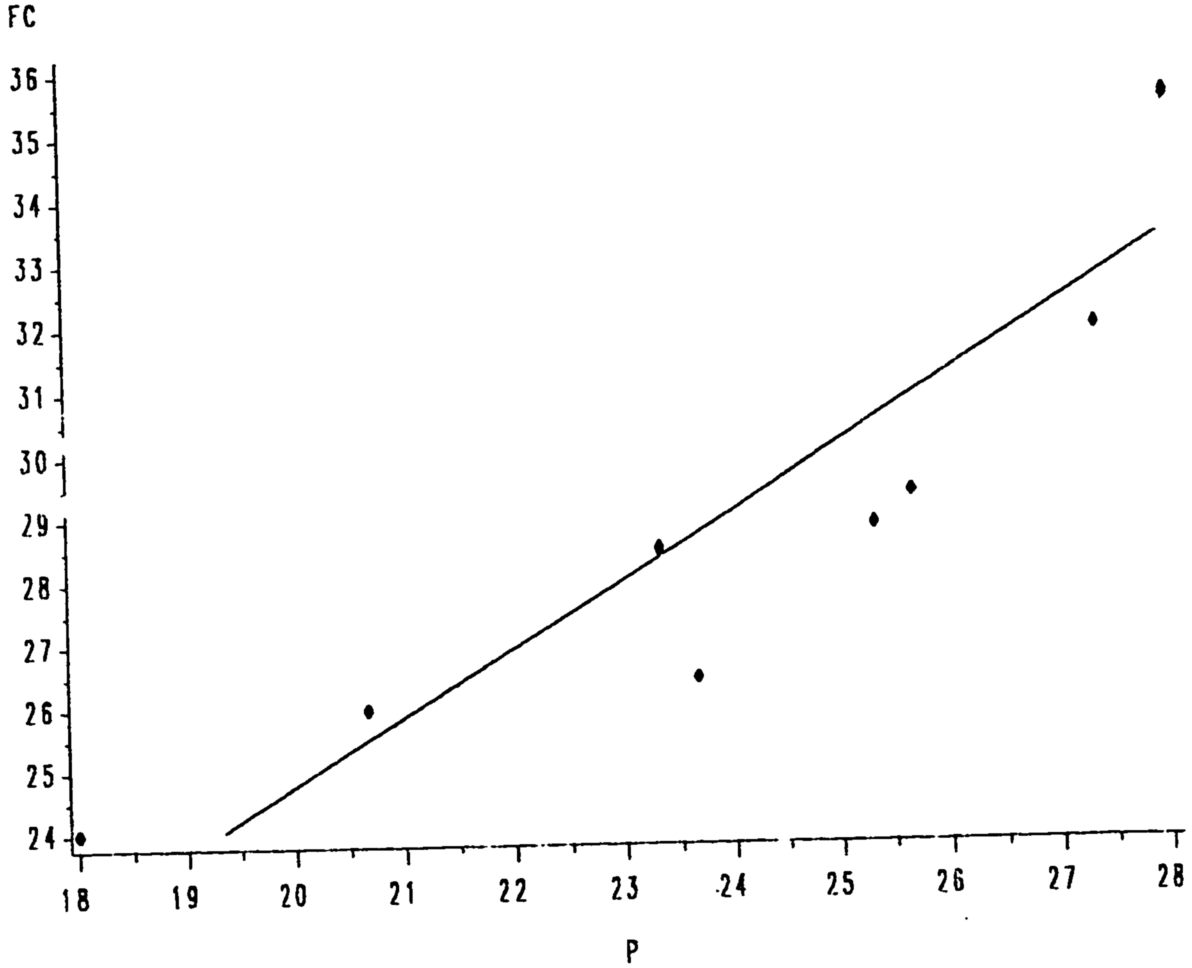
FC=2.97 +1.09 P

FIG. 4.18A: RELATIONSHIP OF COMPRESSIVE AND CAPO STRENGTH FOR ABU-HADRIYAH



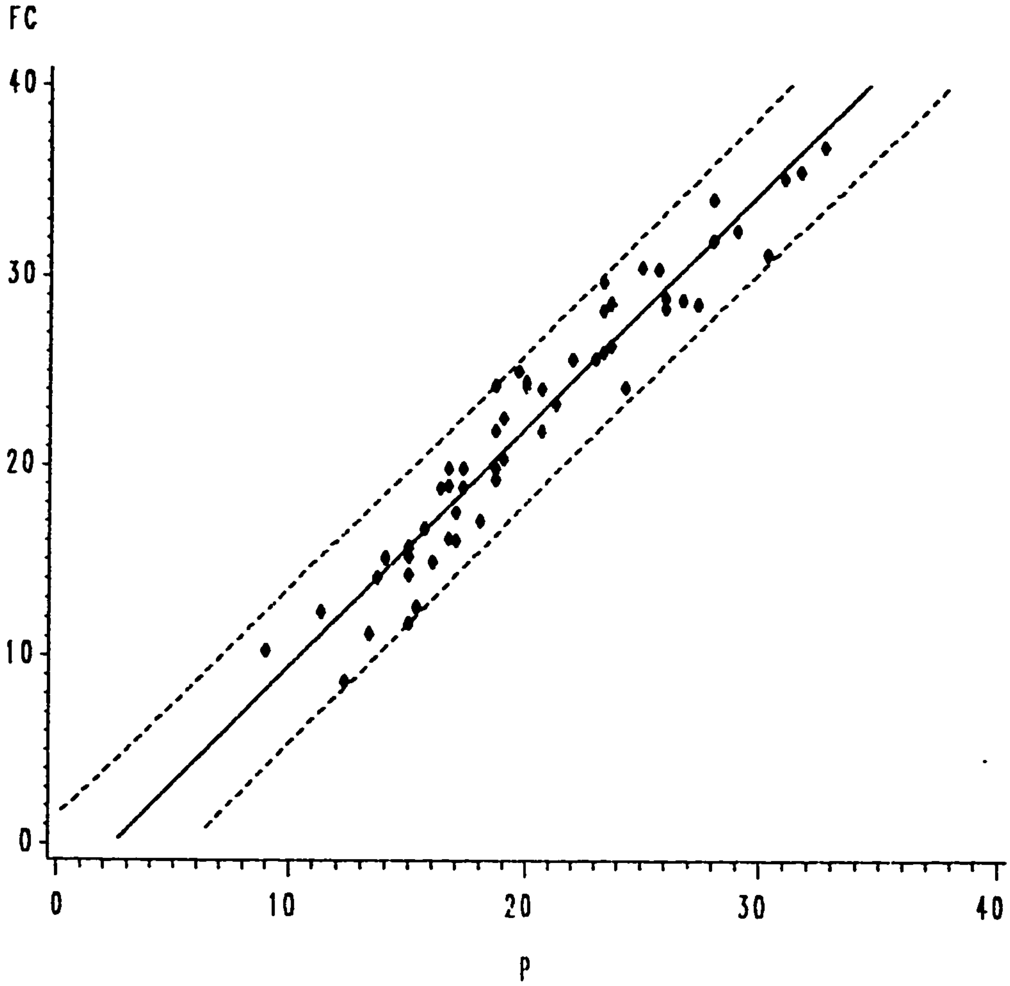
FC=3.89 +1.067 FC

FIG. 4.18B: RELATIONSHIP OF COMPRESSIVE AND CAPO STRENGTH FOR ABU-HAD.,CC=400



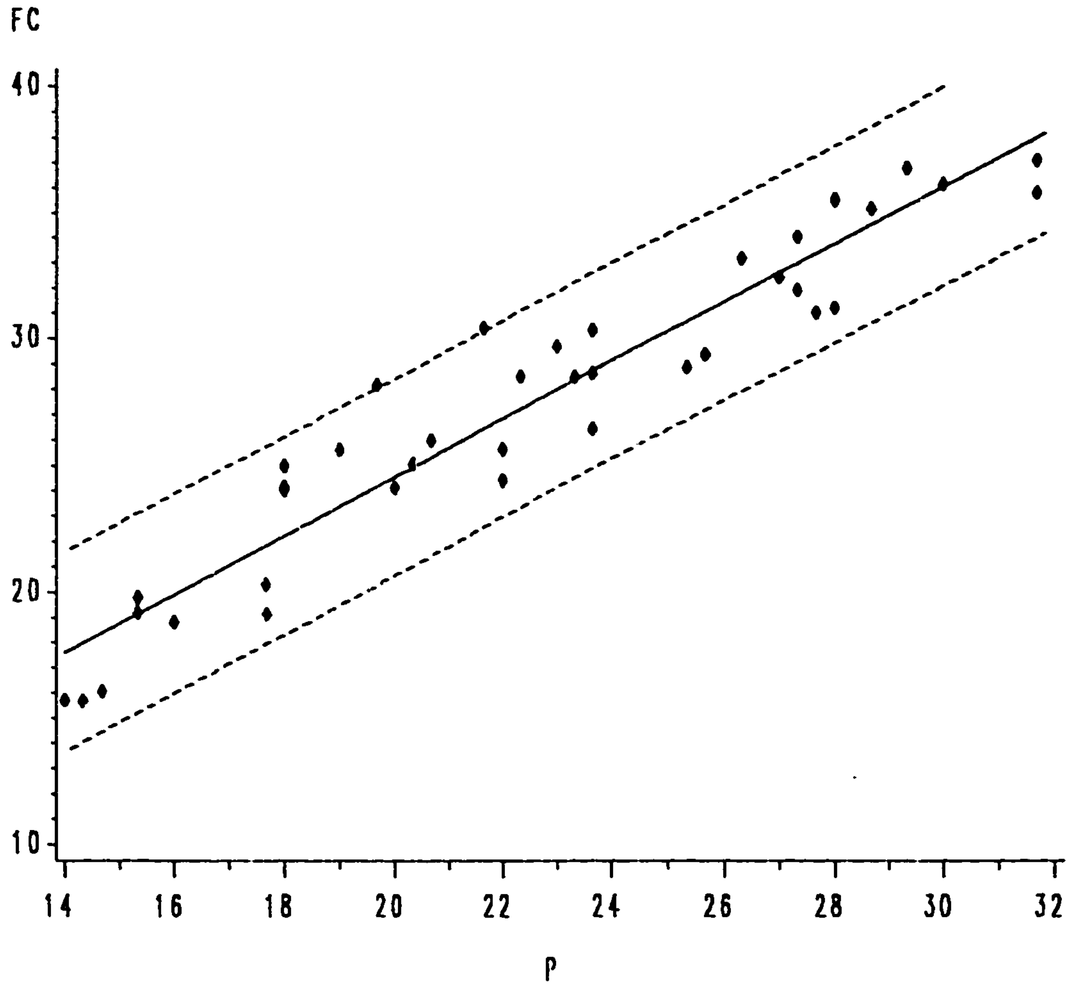
FC =3.20 +1.077 P

FIG. 4.18C: RELATIONSHIP OF COMPRESSIVE AND CAPO STRENGTH FOR ABU-H., CC=300



FC =-2.95 +1.24 P

FIG. 4.19A: RELATIONSHIP BETWEEN COMPRESSIVE AND LOK STRENGTH FOR WHOLE DATA OF DH. AND ABU-H.



FC=1.53 +1.15 P

FIG.4.19B: RELATIONSHIP OF COMPRESSIVE AND CAPO FOR J. DH. AND ABU-HAD.

CHAPTER 5

VERIFICATION OF THE PROPOSED MODELS

5.1 General:

In order to examine the applicability of the proposed model for the in-situ concrete, the model has to be tested with some field data. It was not possible to collect such data exclusively for this purpose due to obvious reasons of cost and practical problems. So that, data was taken from other selected projects, also some panels have been prepared for the verification of the proposed model.

5.2 Core strength versus cylinder strength:

The actual in-situ concrete strength is often determined by cores taken from the structure, and the proposed models are based on cylinder strength, it is necessary to correlate core strength to cylinder strength, as the core strength is known to be slightly less than cylinder strength.

Core samples used for compressive strength determination must be selected carefully so as to be free of any cracks and steel reinforcement, with the length/diameter ratio being kept as close to 2.0 as possible. For the purpose of correlating the cylinder strength to the in-situ strength of the panel of identical mix design, three cores of 75 mm diameter were taken from each two panels at 7, 14, 28 and 91 days. The average compressive strength were measured for cores at each age, so as to compare it with the corresponding values of the standard cylinders.

Tables 5.1 and 5.2 show these data and the ratio of core to cylinder strength, for both Jabel Dhahran and Abu-Hadriyah concrete respectively. From the data in previous tables, it is observed that the core to cylinder strength varied from a maximum of 0.99 to a minimum of 0.73 for Jabel Dhahran, also it varied from 0.97 to .71 for Abu-Hadriyah but most of the data falling within a narrow band. The average value of core strength to cylinder strength is .86 for Jabel Dhahran and .88 for Abu-Hadriyah, indicating a good representation of the average value.

5.3 Verification of the models:

The proposed predictive equations of cylinder compressive strength as follows:

Proposed models by using Jabel Dhahran aggregate:

For Lok strength $F_C=-2.60+1.21P_L$ (5.1)

For Capo strength $F_C=1.18+1.165P_C$ (5.2)

Proposed models by using Abu-Hadriyah aggregate:

For Lok strength $F_C=-2.266+1.23P_L$ (5.3)

For Capo strength $F_C=2.97+1.09P_C$ (5.4)

Proposed models by using both types of aggregate:

For Lok strength $F_C=-2.95+1.24P_L$ (5.5)

For Capo strength $F_C=1.53+1.15P_C$ (5.6)

To examine the applicability of the proposed models for the in-situ concrete, data taken from other mixes, Table 5.3 shows the designation and mix design of the selected panels.

For Jabel Dhahran (DH), slab panels were cast along with some cylinders, by using .55 water cement ratio , and cement contents of 300, 350 and 450 Kg/ M^3 and the maximum aggregate size is 25 or 20 mm (1 or 3/4 inch). 14 inserts for lok-test were fixed in the mold before casting of panels.

Three cylinders were tested for evaluation of 3, 7, 14 and 28 days compressive strength. For some mixes three cores at 7, 14 and 28 days were tested, in addition 3 lok-tests at 3, 7, 14 and 28 days and three capo-tests at 14 and 28 days were performed as shown in Table 5.4 .

For Abu-Hadriyah (AB), two slab panels were cast along with some cylinders, by using .63 water cement ratio , 400 Kg/ M^3 cement content and the maximum aggregate size is 20 mm (3/4 inch). Tables 5.5a and 5.5b shows the average experimental data collected. Also some blocks from another project were tested to verify the Capo calibration, for one of these blocks, the average actual cylinder compressive strength was 8.27 MPa and the average Capo strength was 5.60 kn, and the predicted compressive strength was 7.97 by using Eqn. 5.6 which is close to the actual. Tables 5.6 show verification data by using different types of aggregate from Ras-Alkhima and Riyadh, W/C was 0.55 and cement content was 400 Kg/ M^3.

Using the previous models, The estimated compressive strength has been determined, and the ratio of actual strength to estimated strength was calculated as shown in Tables 5.

It is observed from the previous tables that the proposed models often slightly underestimate the strength of concrete.

In order to know the accuracy of the combined model Eqn. 5.5 for Lok strength, the model has to be compared with the international calibration equation reported in (8) as follows:

$$P=0.90F_c+1.00 \qquad \text{for} 2kN<P\leq 25kN \qquad (5.7)$$

$$P=0.80F_c+5.00 \qquad \text{for} 25kN<P\leq 65kN \qquad (5.8)$$

By writing the above equations in term of Fc:

$$F_c=1.11P-1.11 \qquad (5.7)$$

$$F_c=1.25P-6.25 \qquad (5.8)$$

Tables 5.7a, 5.7b show results of the verification by using different types of aggregate, where the compressive strength values predicted by the proposed Eqn. (5.5) and the international Eqn. (5.7) and (5.8). From Table 5.7a, the average value of Fc actual/Fc estimated is 1.06 and the standard error is 1.57 by using Eqn. (5.5), by using the International Eqn. the average value of Fc actual/Fc estimated is 1.09 and the standard error is 2.43 . In Table 5.7b, the average value of Fc actual/Fc estimated is 1.01 by using Eqn. (5.5) and 1.05 by using the International Eqn., and the standard error is 1.44 and 1.36 respectively, that means the accuracy of both models approximately is the same. Table 5.8 shows the verification of the previous models Eqn. (5.5) and (5.6) by using data from Denmark Ref.(30), the average value of Fc actual/Fc estimated is 1.04 and .97, the standard error is 2.22 and 2.19 respectively for the previous mdels which means that the reliability and accuracy of lok and capo models are close to each other.

Table 5.1a: Experimental data for Jabel Dhahran aggregate concrete for cement content= 300 kg/ m^3.

W/C	AGE (days)	COR (MPa)	FC (MPa)	COR/FC
.70	7	9.92	12.32	.81
.70	14	14.44	15.69	.92
.70	28	18.67	18.81	.99
.65	7	10.47	12.55	.83
.65	14	15.07	16.03	.94
.65	28	16.57	19.21	.86
.65	91	16.21	19.15	.85
.55	7	18.35	21.81	.84
.55	14	21.81	24.96	.87
.55	28	23.34	25.58	.91
.55	91	19.71	25.04	.79
.45	7	16.45	17.52	.94
.45	14	23.00	24.11	.95
.45	28	23.23	28.50	.82
.45	91	25.79	28.61	.90

Table 5.1b: Experimental data for Jabel Dhahran aggregate concrete for cement content= 400 kg/ m^3.

W/C	AGE (days)	COR (MPa)	FC (MPa)	COR/FC
.70	7	12.55	14.21	.88
.70	14	15.50	16.66	.93
.70	28	18.47	19.80	.93
.65	7	16.19	18.79	.86
.65	14	18.07	20.32	.89
.65	28	20.41	24.15	.85
.65	91	22.10	24.38	.91
.55	7	16.58	19.86	.84
.55	14	20.61	28.15	.73
.55	28	24.87	30.39	.82
.55	91	27.31	33.15	.82
.45	7	22.43	28.28	.79
.45	14	26.02	31.17	.84
.45	28	27.70	35.11	.79
.45	91	29.06	35.75	.81

Table 5.2a: Experimental data for Abu-Hadriyah aggregate concrete for cement content = 300 kg/ m^3.

W/C	AGE (days)	COR (MPa)	FC (MPa)	COR/FC
.65	7	19.09	19.80	.96
.65	14	23.92	24.02	.996
.65	28	22.85	25.94	.88
.65	91	25.68	26.41	.97
.55	7	20.48	24.25	.84
.55	14	22.11	28.47	.78
.55	28	23.44	28.83	.81
.55	91	25.89	29.33	.88
.45	7	23.53	28.70	.82
.45	14	26.88	31.87	.84
.45	28	30.43	35.43	.86
.45	91	32.15	35.50	.91

Table 5.2b: Experimental data for Abu-Hadriyah aggregate concrete for cement content = 400 kg/ m^3.

W/C	AGE (days)	COR (MPa)	FC (MPa)	COR/FC
.65	7	20.32	22.49	.90
.65	14	22.66	25.62	.88
.65	28	26.66	30.30	.88
.65	91	28.10	30.99	.91
.55	7	21.23	21.78	.97
.55	14	24.25	30.43	.80
.55	28	25.16	35.33	.71
.55	91	32.82	36.09	.91
.45	7	25.43	28.58	.89
.45	14	27.56	30.51	.90
.45	28	32.64	35.89	.91
.45	91	35.04	37.05	.95

Table 5.3: Designation and mix proportions for concrete.

DESIGNATION	CEMENT CONTENT kg/cu m	CA/FA	W/C	MAX SIZE OF CA (in.)
DH1	300	1.68	0.55	1
DH2	350	1.63	0.55	3/4
DH3	450	1.63	0.55	3/4
AB	400	1.63	0.63	3/4

Table 5.4a: Experimental data for Jabel Dhahran (DH1) aggregate concrete for verification of Lok, CC=300

days	actual lok (kN)	actual FC (MPa)	estimated Fc by Eq. 5.5	estimated Fc by Eq. 5.1	Fc act/est by Eq. 5.5	Fc act/est by Eq. 5.1
14	25	26.08	26.05	27.65	0.93	0.94
28	28	30.63	31.77	31.28	0.96	0.98

Table 5.4b: Experimental data for Jabel Dhahran (DH1) aggregate concrete for verification of Capo, CC=300

days	actual cap (kN)	actual FC (MPa)	estimated Fc by Eq. 5.6	estimated Fc by Eq. 5.2	Fc act/est by Eq. 5.6	Fc act/est by Eq. 5.2
14	22	26.08	26.83	26.81	0.97	0.97
28	24	30.63	29.13	29.14	1.05	1.05

Table 5.4c: Experimental data for Jabel Dhahran (DH2) aggregate concrete for verification, CC=350

days	actual lok (kN)	actual FC (MPa)	estimated Fc by Eq. 5.5	estimated Fc by Eq. 5.1	Fc act/est by Eq. 5.5	Fc act/est by Eq. 5.1
7	18	22.34	19.37	19.18	1.15	1.16
14	19	25.16	20.61	20.39	1.22	1.23
28	22	27.70	24.68	24.02	1.12	1.15

Table 5.4d: Experimental data for Jabel Dhahran (DH3) aggregate concrete for verification, CC=450

days	actual lok (kN)	actual FC (MPa)	estimated Fc by Eq. 5.5	estimated Fc by Eq. 5.1	Fc act/est by Eq. 5.5	Fc act/est by Eq. 5.1
7	19	22.39	20.61	20.39	1.09	1.10
14	25	27.00	28.05	27.65	0.96	0.98
28	25	29.90	28.05	27.65	1.07	1.08

Table 5.5a: Experimental data for Abu-Hadriyah aggregate for verification of Lok models, CC=400

days	actual lok (kN)	actual FC (MPa)	estimated Fc by Eq. 5.5	estimated Fc by Eq. 5.3	Fc act/est by Eq. 5.5	Fc act/est by Eq. 5.3
7	15	17.28	15.65	16.18	1.10	1.07
14	18	20.75	19.37	19.87	1.07	1.04
28	19.67	23.1	21.44	21.93	1.08	1.05

Table 5.5b: Experimental data for Abu-Hadriyah aggregate for verification of Capo models, CC=400

days	actual cap (kN)	actual FC (MPa)	estimated Fc by Eq. 5.6	estimated Fc by Eq. 5.4	Fc act/est by Eq. 5.6	Fc act/est by Eq. 5.4
14	15	20.75	18.78	19.32	1.18	1.14
28	16	23.1	19.93	20.41	1.16	1.13

Table 5.6a: Experimental data for Ras-Alkhima aggregate

days	actual Lok (kN)	actual Capo (kN)	actual FC (MPa)	estimated FC by Eq. 5.5	estimated FC by Eq. 5.6	Fact/Fest by Eq. 5.5	Fact/Fest by Eq. 5.6
3	14.67		15.34	15.24		1.01	
7	18.67		21.35	20.20		1.06	
14	21.00	22.33	25.41	23.09	27.21	1.10	.93
28	25.00	26.33	29.84	28.05	31.81	1.06	.94

Table 5.6b: Experimental data for Riyadh aggregate

days	actual Lok (kN)	actual Capo (kN)	actual FC (MPa)	estimated FC by Eq. 5.5	estimated FC by Eq. 5.6	Fact/Fest by Eq. 5.5	Fact/Fest by Eq. 5.6
3	15.00		16.77	15.65		1.07	
7	1[illegible].33		22.38	21.02		1.06	
14	24.00	24.67	26.61	26.81	29.90	.99	.89
28	29.00	27.67	30.74	33.01	33.35	.93	.92

Table 5.7a: Experimental data for Ras-Alkhima aggregate

days	actual Lok (kN)	actual FC (MPa)	estimated FC by Eq. 5.5	estimated FC by Int Eq. 5.7	Fact/Fest by Eq. 5.5	Fact/Fest by Int. Eq. 5.7
3	14.67	15.34	15.24	15.17	1.01	1.01
7	18.67	21.35	20.20	19.61	1.06	1.09
14	21.00	25.41	23.09	22.20	1.10	1.15
28	25.00	29.84	28.05	26.64	1.06	1.12

Table 5.7b: Experimental data for Riyadh aggregate

days	actual Lok (kN)	actual FC (MPa)	estimated FC by Eq. 5.5	estimated FC by Int Eq. 5.7	Fact/Fest by Eq. 5.5	Fact/Fest by Int. Eq. 5.7
3	15.00	16.77	15.65	15.54	1.07	1.08
7	19.33	22.38	21.02	20.35	1.06	1.10
14	24.00	26.61	26.81	25.53	.99	1.04
28	29.00	30.74	33.01	30.00	.93	1.02

Table 5.8: Vereficiation of the proposed models. Data from Ref.(30).

No.	actual Fc (MPa)	actual Lok(kN)	actual Capo(kN)	estimated FC by Eq. 5.5	estimated FC by Eq. 5.6	Fact/Fest by Eq. 5.5	Fact/Fest by Eq. 5.6
1	25.40	22.70	21.10	25.20	25.80	1.00	0.98
2	24.70	21.80	21.20	24.08	25.91	1.03	0.95
3	26.30	22.70	24.20	25.20	29.36	1.04	0.90
4	24.90	22.60	22.90	25.07	27.87	0.99	0.89
5	28.80	22.40	25.80	24.83	31.20	1.16	0.92
6	37.40	33.00	32.80	37.97	39.25	0.98	0.95
7	33.00	30.00	29.10	34.24	35.00	0.96	0.94
8	40.20	32.80	30.90	37.72	37.07	1.07	1.08
9	39.30	31.30	31.80	35.86	38.10	1.10	1.03
10	40.20	32.00	31.90	36.73	38.22	1.09	1.05
		average				1.04	.97

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary:

An elaborated test program was conducted in this study to develop strength prediction models, using the results of Lok-test and Capo-test in the Eastern region of Saudi Arabia. Based on the regression analysis of test data generated from concrete panels made with Jabel Dhahran and Abu-Hadriyah coarse aggregate, linear relationships relating compressive strength to Lok and Capo strength are produced. The proposed models have been verified for their reliability by comparing predicted strength by actual strength.

6.2 Conclusions:

1) It is clear that a linear relationship exists between compressive strength of cylinders and Lok and Capo loads with high coefficient of correlation almost above (0.90).
2) It can be concluded that age, W/C ratio, cement content and type of aggregate do not affect the relationship between cylinder compressive strength and Lok or Capo

strength.

3) The proposed models of Lok and Capo tests can be used to predict the strength of in-situ concrete made with Jabel Dhahran or Abu-Hadriyah aggregate in the Eastern Region of Saudi Arabia.

4) The next combined models of Jabel Dhahran and Abu-Hadriyah

   For Lok strength $F_C = -2.95 + 1.24P_L$ (5.5)

   For Capo strength $F_C = 1.53 + 1.15P_C$ (5.6)

   can predict the strength of in-situ concrete made by using different type of aggregate with an acceptable degree of accuracy.

5) The within-test variations of cylinder compressive strength, Lok and Capo strength are within the acceptable limits, where coefficients of variation are almost less than 10% .

6.3 Recommendation :

Further research is needed in future to develop more accurate combined models by using different variables in the Kingdom such as:

1) More aggregate sources around the Kingdom.
2) Carbonation effect.
3) Maximum aggregate size.
4) High strength concrete.
5) Bleeding effect.
6) Position and orientation of pull-out test.
7) Effect of steel cover.

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